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Physical characteristics and aquatic settlement properties of offshore drill-cuttings.

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PHYSICAL CHARACTERISTICS AND AQUATIC SETTLEMENT PROPERTIES OF OFFSHORE DRILL-CUTTINGS

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A thesis submitted in partial fulfilment of the requirements of the Robert Gordon University for the degree of Doctor of Philosophy

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ABSTRACT

Drilling operations have been proven to cause pollution in the marine environment. From these environmental concerns, regulations and drilling muds evolved towards more environmental orientated operations. The environmental impact assessment is now compulsory and made public. In order to carry out some aspects of this assessment, environmental engineers run models for the prediction of the wastes dispersion into the sea. The existing models have been studied and two main points were observed:

- the required input data on cuttings characteristics was not available for specific drilling conditions, and;
- the settling properties of the particles was not adapted to the type of modelled particles.

There was no readily available information about correlations between the cuttings size and the drilling parameters. Moreover, there was no study on the settlement of cuttings made on a large number of real drill-cuttings. From these observations, it was clear that the cuttings characteristics needed to be studied under different drilling conditions. The aquatic settlement properties of the cuttings also became a focus of the present study. A spontaneous and long-term enthusiasm from the oil industry made the study possible. The collection of samples and data was then carried out prior to laboratory experiments. From these experiments, the characteristics (i.e. size and shape) of cuttings were defined as well as the cuttings settling speeds. The new data on settling speeds was then analysed by comparison with other experimental works, correlations for settling speeds and drag correlations. Computational work also confirmed the need for a better adapted drag correlation. Therefore, based on the experimental data, a new drag correlation was determined. It is believed to be valid for cuttings of any shape for Reynolds number up to 1000.

The cuttings size distributions drawn from experiments were also analysed using a commercial statistical package. From this analysis, new correlations between the cuttings size and the drilling parameters were defined. The quality, robustness and limitations of these correlations are discussed. Each model was carefully assessed and improved until satisfaction. A Fortran 90 program was then written to support the database. The program asks for input data from the user and returns the cuttings size distributions as output data. It interpolates incoherent data and advises the user to change the combination when required. It also gives information about the new drag correlation and average sphericity for drill-cuttings.

The present work contributes to the knowledge of physical characteristics and aquatic settlement properties of offshore drill-cuttings. It is based only on offshore samples and data which makes its originality. There are many applications of the findings both in the drilling and environmental engineering. Some of the findings have already been incorporated in commercial software for environmental consultancy. Nevertheless, there is place for further work on this fascinating subject. Recommendations are made, based on ranging experiments and criticism of the present work.

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NOMENCLATURE

m: mass of the particle (kg)
V_p : volume of the particle (m^3)
v_p : velocity of the particle ($m.s^{-1}$)
ρ_f : density of the fluid ($kg.m^{-3}$)
ρ_p : density of the particle ($kg.m^{-3}$)
d_p : diameter of the particle (m)
C_D : drag coefficient (dimensionless)
R_{ep} : Reynolds number of the particle (dimensionless)
μ_f : viscosity of the fluid ($kg.m^{-1}.s^{-1}$)
g: gravity (9.81 $m.s^{-2}$)

ABBREVIATIONS

BHA: Bottom Hole Assembly
CFD: Computational Fluid Dynamic
EIA: Environmental Impact Assessment
LSM: Least Square Method
MD: Measured Depth
OBM: Oil-Based Mud
PDC: Polycrystalline Diamond Compact
ROP: Rate of Penetration
RPM: Revolution Per Minute
SBM: Synthetic-Based Mud
SG: Specific Gravity
SMOE: School of Mechanical and Offshore Engineering
TVD: True Vertical Depth
UKCS: United Kingdom Continental Shelf
UKOOA: United Kingdom Oil Operators Association
WBM: Water-Based Mud

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Chapter.1
BACKGROUND

1.1 INTRODUCTION

Oil and gas, as found in nature, are naturally trapped underground within the myriad microscopic pores of reservoir rocks into which they migrated from source rocks over a period of millions of years. They are derived almost entirely from decayed plants and bacteria. When the source rocks start to generate oil or gas, it is said to be 'mature' (UKOOA 1997). These source rocks were themselves deposited in ancient seas, rivers or lakes. Impervious sediments which were deposited on top of the porous reservoir formations sealed the reservoir underground, preventing (not always) the hydrocarbons from seeping away to the surface. Oil and gas are not found in liquid 'pools', but are found within the pores of a porous rock such as sandstone, much as a sponge holds water, trapped under very high pressure. To reach underground oil and gas, operators drill boreholes (i.e. wells) through subterranean rock, generally up to several thousand metres thick, making wells. Then, they complete the well by installing production tubing. The oil and gas is released from the pressure of the rock and rises up the drilled well.

During drilling operations, it is necessary to pump a fluid down the hole to aid in the drilling process. Generally called 'drilling mud' because of its physical appearance, this fluid consists of water, various special chemicals and frequently a weighting element (e.g. barite). This fluid is continuously circulated down the well, and back up to the surface of the rig. One of the functions of these muds is to carry the rock chips (drill-cuttings) back to the rig for treatment and discharge. The detailed circulating system is presented in the next section of this chapter. As a brief summary, it can be said that the cuttings brought to the platform are separated from the mud, which is recycled to be used again, and the cuttings plus some remains of the drilling muds are, most of the time, discharged directly to the sea.

In exploring for and producing hydrocarbons, the oil industry, in just over a century, has developed its own special equipment and skills for remotely probing the earth's crust. As the need for energy in easily transported forms has grown in step with the expansion of industrial and transportation activity, so the search for hydrocarbons has intensified. With that intensification has come greater knowledge and understanding of the conditions under which oil and gas were formed and are found, and of the methods by which optimum recovery can be made. In the last few decades, the search has moved into offshore waters, and into greater depths (The Petroleum Handbook 1983). The industry has called for knowledge in other fields in order to conduct its business- in diving, medicine, meteorology, engineering design and construction, helicopter operations, subsea pipeline design and construction, and more recently environmental sciences.

For example more than 15% of the world's total petroleum production is currently from offshore wells. This percentage is expected to increase rapidly during the next decade. There are already several major petroleum producing regions located offshore of the major continents. In Europe for example, more than 90% of the production comes from offshore fields. The North Sea hydrocarbon producing industry began in 1959 with the discovery of the Groningen onshore gas field by Shell in the Netherlands. Exploration wells drilled in England revealed similar rock strata, indicating that large hydrocarbon reservoirs could exist in the southern basin of the North Sea. The West Sole gas field was a significant discovery and the first gas was brought ashore in 1967. Continued exploration of the Southern Basin showed that the hydrocarbon accumulations were predominantly gaseous and exploration activities moved farther north to the central North Sea and the East Shetland Basin. Discoveries of exploitable oil reserves quickly followed, the first being the Ekofisk field in the Norwegian Sector in 1969 followed by Montrose (1969), Forties (1970) and Brent (1971) in the UKCS (UKCS: United Kingdom Continental Shelf). The first oil discovered in the Danish sector was at the Dan field (1971) (The Petroleum Handbook 1983). Since then there has been a proliferation of developments with over 150 installations currently in place.

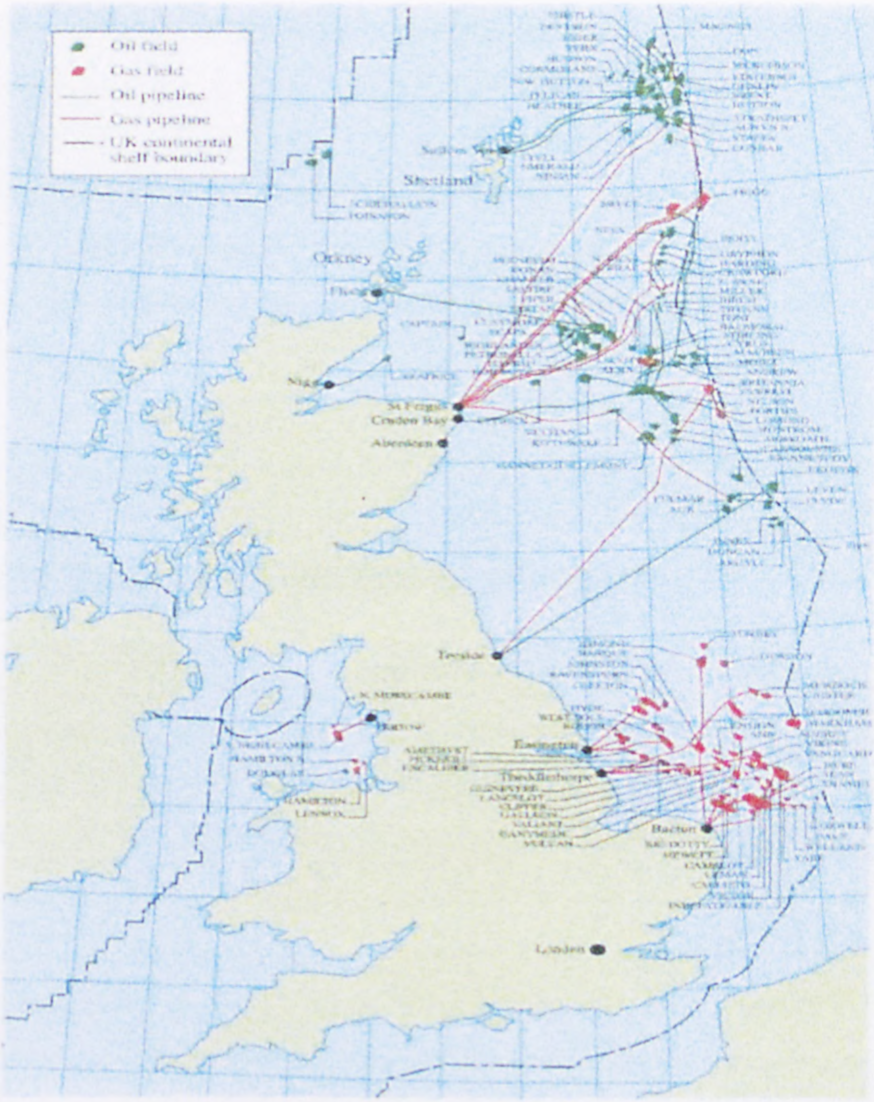


Figure 1.1: A map of the North Sea major oil and gas fields (UKOOA 1997).

In this extended search beneath the ocean's surface, an already sophisticated and complex petroleum technology was further expanded as a host of new environmental problems were encountered. New questions were raised and one of them was: 'To what extent do drilling and production operations pollute the marine environment?'. To address these questions and other related matter, a new exciting marine petroleum technology has developed in response to the challenging environmental concerns encountered beneath the surface of the world's oceans.

Before exploitation, operators conduct exploration using seismic surveys and other methods to identify potential reservoirs. Then, when new oil and gas in the subsurface is located, an exploration well is drilled. If conditions are satisfactory, production wells are drilled and oil or/and gas is produced. In the North Sea, oil fields tend to be located in the North and gas fields in the South of the North Sea. Before starting any type of works in the Scottish sector of the North Sea, oil and gas companies need permission from SOAFD (Scottish Office for Agriculture and Fisheries Department). Generally speaking, the applicant has to state the details of the work and its potential harm to the environment in a document called PON 15 (DTI 1998).

The release of wastes from offshore drilling operations raises the potential for damage to the marine habitat and the many organisms that it supports. Existing cuttings discharges have resulted in cuttings piles on the seabed which may be harmful to the marine life and expensive to remove at platform abandonment time. Conflicts with other traditional users of the continental shelf can result, especially when proposed drill operations are located within, or adjacent to, highly productive and commercially important fishing grounds. Resolution of such conflicts requires an understanding of the environmental processes that affect wastes after discharge and the development of reasonable regulatory procedures based on sound scientific information (Carles 1996). Drilling wastes contain rock fragments contaminated with drilling muds. The contamination can include hydrocarbons as well as other products, like bentonite, which are potentially hazardous, especially to the benthic community. When drilling discharges are released into the water column, they are subjected to a wide variety of mixing and transport processes. In order to determine the areas potentially at risk from drilling operations and prevent possible conflicts between different users of the sea, it is necessary to understand the complex physics of these processes to be able to predict the behaviour of the released particulate matter. The behaviour of relatively large drill-cuttings is well-defined but that of the fine particulates is still described unprecisely, mainly because of the difficulty in quantifying the processes of aggregation and turbulence.

In order to fully ascertain the impact of drilling development, it is necessary to determine accurately the dispersion of the drilling discharge into the sea. The development of a dispersion model would enable the determination of the different concentrations of drilling waste particulate (commonly called 'drill-cuttings')- of any size and shape- deposited on the seabed or the thickness of the cuttings pile on the seafloor. Some models already exist and could be improved to achieve a more accurate model which would predict the behaviour of even fine particulates into the water column and their deposition on the seafloor (Carles and Bryden 1997). Questions about the relevance of the required input data for this type of models have arisen:

- is the input data in the adequate form for the user?;
- is it possible for the user to provide such data without using 'guesstimates'?, and;
- is the required input adequate to solve the relevant equations?.

A better knowledge of drill-cuttings characteristics would result in more accuracy and appropriateness of the input data and therefore of the output data. Some correlations between drill-cuttings characteristics and drilling parameters could be obtained from historical data, surveys on new wells and laboratory experiments.

Chapter.1 states the needs for a better knowledge of the cuttings characteristics. In order to use any model involving the transport of cutitngs, the size, the shape and the density of cutitngs are vital input data. Correlations between these characteristics and the drilling conditions would tremenduously help the users of cuttings transport simulations. The settlement of those particles is also of great importance. In effect, the analysis of their settlement in water gives precious information especially on the drag coeffcient. Chapter.1 also presents the objectives and outline the content of the thesis.

1.2 REQUIREMENTS FOR THE WORK

1.2.1 Environmental Impact Assessment

Environmental concerns from offshore operations are becoming a very serious issue for oil companies all over the world. An amazing amount of work has been carried out in Europe, China and Canada. For example, in Canada, due to concerns over potential impacts on valuable fisheries resources, there is a moratorium on drilling on Georges Bank until at least the year 2000 (Gordon *et al* 1992). In order to know more about the impacts of cuttings discharge, more information is necessary about the cuttings themselves, their dispersion in the water column and the way they disturb the surrounding environment. This document only deals with the urgent need to better describe the characteristics of the discharged material.

In the worst case situation, the amount of oil-based drilling fluid attached to the cuttings discharged is approximately 75 to 100 tons of oil per well (Mulder 1988). These data show the enormous amount of oil discharged from drilling operations into the North Sea and therefore, the importance of estimating the impacts of oil contamination on the marine environment. It is recognised that potential impacts will depend very much upon the environmental conditions of the drill site -which can change markedly with time- and the biogeochemical behaviour of wastes once released into the seawater. Predicting the extent of impact zones around drilling platforms requires the intelligent integration of physical, sedimentological, chemical and biological information. Experience has shown that this can be accomplished most effectively by constructing multidisciplinary impact assessment models (Cranford *et al* 1992). This is why the present work concentrated on the characteristics of drill-cuttings and the study of their settlement in water.

The assessment of impacts of marine contaminants should include clear predictions of transport processes and rates, the environmental compartments where contaminants will concentrate, the chemical composition and concentration of contaminant, and the likely biological impacts that contaminants will have on target species (Cranford *et al* 1992). In the legal documentary, it is specified that the EIA (introduced in section 1.3.1) should include 'a description of the likely significant effects, direct and indirect, on the environment of the development, explained by reference to its possible impact (where applicable) on- [...] flora, fauna, soil, water [...].' (DTI February 1998).

In order to predict the environmental impacts of the drilling wastes, companies must first define, with accuracy, the fate of the contaminants in the water column. Usually, the EIA is written by a consultancy company, independent from the oil company. The consultants need to answer the following questions:

- what is discharged?
- how much is discharged?
- how is it discharged?
- where is it discharged?
- when is it discharged?
- what are the processes of the physical dispersion?

- what characteristics of the discharge will influence the dispersion?
- what characteristics of the marine environment will influence the dispersion?

To obtain an answer to all these questions, a close collaboration between the consultants conducting the EIA and the oil company is necessary. The consultants need to have a general drilling program and as much information as possible about the drilling of the well, the shipping routes or pipelines. They need to simulate the dispersion of oil in case of an oil spill and the dispersion of drilling wastes after discharge. Some computational models have been and are being developed to predict the impacts of offshore activities on the marine environment (e.g. the software 'Proteus' by BMT).

1.2.2 Existing dispersion models

In order to determine the impacts from drilling operations, it is necessary to understand the physical dispersion of the drilling discharge into the sea. The development of a waste dispersion model enables the prediction of the concentrations of drill-cuttings deposited on the seabed and the thickness of the cuttings pile (if present) on the seafloor. The sophisticated models use firstly a hydrodynamic model to describe the marine environment. Then, they need to simulate the dispersion in the water column and finally the behaviour of material in the benthic boundary layer (see Figure 1.2).

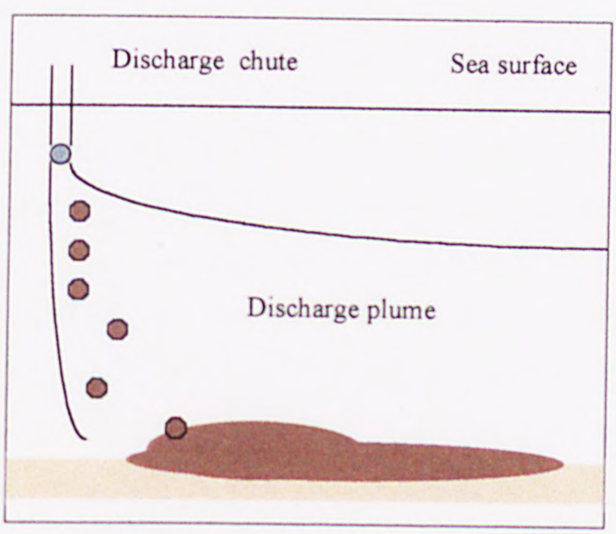


Figure 1.2: The transport of discharged material into the sea.

The discharged material is normally specified in terms of its settling speed distribution (mass fraction versus settling speeds) and bulk density (Spaulding 1994). The value of the settling speed determines the length of time that the particle spends in the water column and therefore its deposition point on the seabed. So, model results are very sensitive to the values assumed for fall velocity (big difference between using 1cm/sec and 2cm/sec) (Gordon *et al* 1995). Models could be improved by using more appropriate equations for the cuttings settling speeds and by requiring better adapted input data. Oceanographic data, location, point of discharge and drilling parameters are generally not a problem to get for a specific project. Drill-cuttings characteristics, however, are very difficult to determine months before drilling, even if this information is vital to preserve the precision of the model. Therefore, in most cases, consultants are forced to use guesstimates. The usual guesstimates are that the cuttings are spherical, of a limited range of size and with a unique density. Correlations between drill-cuttings and drilling parameters can be determined and introduced in a database used as input rather than guesstimates (Carles and Bryden 1998). The most sensitive parameter, 'size profile', is the most difficult to determine in advance of a drilling operation. If advanced predictions of environmental impacts are to be made, it will be necessary to conduct a correlation analysis of geological and drilling parameters with discharge characteristics over as wide a range as possible (Bryden and Carles 1998).

Some dispersion models are today available to predict the dispersion of discharged material into the sea (Carles 1996). Most of the existing models (Bryden and Carles 1998, Spaulding 1994, Minton *et al* 1993, Brandsma 1994, BMT 1996 and Shell 1995) require the same input data and give out similar output data. Usually, to perform a simulation, the user must define the operational area, parameters that describe the discharge material and procedure, and environmental conditions that characterise the area and time period of interest. The input data relates to the discharge conditions and the environment conditions. The outputs are generally graphical and represent contour profiles of the drill-cuttings concentrations on the seabed or thickness of the cuttings pile (if present) (see Figure 1.3).

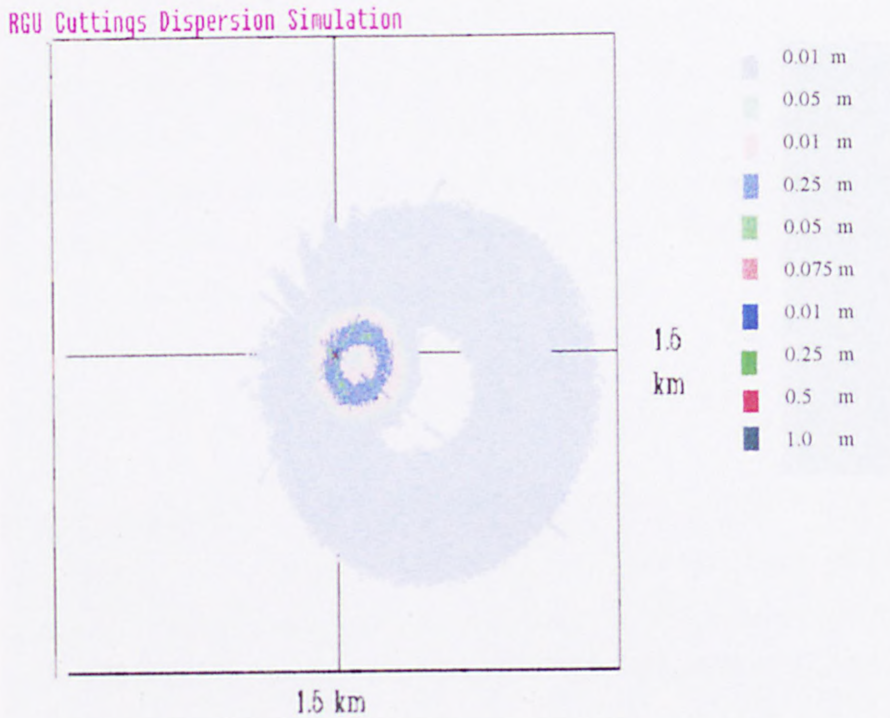


Figure 1.3: Example of a 2D mapping of thickness profiles (in meters) from a dispersion model (Carles and Bryden 1999).

The main points of criticism of existing models can be summarised as follows (Carles 1996):

- very simplistic approach of the hydrodynamics of the marine environment;
- lack of consideration for processes like flocculation/aggregation and turbulence;
- non-acceptable accuracy and appropriateness of the required input data, and;
- non adequate equations for the settling speeds of particles.

In 1998, a study by Bryden and Carles emphasised the sensitivity of a cuttings dispersion model to the cuttings size profile and the oceanographic data. It demonstrated that depending on the cuttings size ranges and the mean current velocity considered, the output could be drastically different.

In 1999, Carles and Bryden also showed that the cuttings dispersion model is very sensitive to the settling speed equation solved by the model. Depending on the correlation used, the output data, under constant conditions, can be very different. This means that depending on the equation and the model used, the cuttings pile, under the same conditions, will have a different shape at a different location. This subjectivity could be overcome by determining the settlement properties of real cuttings. Then, from the analysis of these properties, a more appropriate equation can be found and introduced in the models.

1.2.3 Other applications

There are numerous applications to a better knowledge of drill-cuttings characteristics and settlement properties. For example, hole-cleaning prediction packages should always require the size of cuttings as input from the user. If it does not, then the system assumes that cuttings are either not part of the process or that they all have the same size. None of these two conditions are true in reality. The transport of drill-cuttings in the annular space between the borehole and the drill-pipe (see Chapter.2) is of concern when performance of drilling a well is concerned. The ability to predict the transport of cuttings in the annular space enables to anticipate low performance, cuttings bed formation and improve the planning of the well.

If the characteristics of cuttings are known under different drilling conditions, it also means that simulations can be run under different conditions to study the sensitivity of a drilling parameter for example. Models predicting the pressure drop as a function of the drilling parameters would certainly benefit from such information.

Concerning environmental impacts, it is believed that the knowledge of cuttings size would improve assessing the impacts on certain species for example. If the percentage of cuttings of certain size was known, it would be easier to study which species would be affected and to which extent. Moreover, if the dispersion can be evaluated with more accuracy, the impacts on surrounding fauna and flora will be better assessed. This is very important information to design seabed surveys, to conduct EIA or even to design laboratory experiments.

1.2.4 Summary

As a conclusion, it can be said that nowadays the oil companies have a lot of reasons to worry about environmental impacts of their offshore operations:

- the impacts of the fauna and flora, fish and scallops have been proven by scientific studies;
- new regulations are in place, and also;
- they need to preserve the image received by the general public and handle the pressure from 'green groups'.

Over the past decades, oil companies have been more and more mediatic and public opinion is an important factor of their business. Everyone will remember the noticeable embargo conducted by some Europeans on Shell products after the Brent Spar affair. Another example is the amazing BP's 83-page Environmental Assessment and five-volume oil spill contingency plan for Foinaven and the other Atlantic Frontier developments (Wills 1994).

The evolution of exploration and production offshore operations raises the problem of environmental pollution. Scientific (physical, chemical and biological) studies have been conducted to prove significant impacts on the marine environment from drilling operations. This evolution and the significant environmental impacts are discussed in the next chapter.

Cuttings characteristics and settlement properties are vital inputs to run any simulation involving cuttings transport. However, so far, very little information was known about drill-cuttings characteristics under specific drilling conditions. A better knowledge of such correlations would enable models to ask for relevant and adequate input data. It would also give the possibility to drilling engineers to study cuttings transportation in different cases under different drilling conditions. Also, it has been proven that settlement properties of the cuttings influence a great deal the final output of dispersion simulations. Therefore, there is an urgent need to determine the settlement properties of real drill-cuttings. For the stated reasons, the objectives presented in the next section were defined for the present work.

1.3 OUTLINE OF THE PRESENT WORK

1.3.1 Objectives

From the requirements stated in the previous section, the objectives of this study were numerous and various. They were to:

- understand and build up knowledge on each subject needed for this study: drilling systems, drill-cuttings characteristics, settlement of particles, available prediction models for drilling waste dispersion;
- characterise (through experiments) drill-cuttings sampled on different offshore installations in the North Sea (mainly North and Central North Sea);
- determine the settling speed of drill-cuttings in water;
- develop a new correlation for the drag coefficient of drill-cuttings;
- validate the experimental settling speed values and the new correlation;
- analyse the data from experiments and field survey in order to determine correlations between drill-cuttings characteristics and drilling parameters;
- create a new database that predicts the drill-cuttings size distribution when the drilling parameters are given and advise on settlement properties;
- conclude and suggest further work.

1.3.2 Outline of the thesis

This section presents an overview of the contents of the thesis. The main idea for each chapter is briefly given. First, Chapter.1 presented a general background of the problem. The needs for the present work were stated to emphasise the numerous applications of the present results. It finally gave the objectives of the thesis.

In Chapter.2, detailed information is available to understand the relevant drilling systems and techniques. This is important to fully appreciate the work done on the correlations between the cuttings characteristics and drilling parameters (presented in Chapter.6). Environmental concerns and impacts are presented as well as the existing dispersion models. The evolution of regulations and drilling muds is described to show a growing awareness and effort from operators and mud and service companies. All the information strengthens the needs to know better the drill-cuttings characteristics and their settlement properties.

Chapter.3 describes the process of the collection of data: through an offshore survey and experimental work. The equipment and detailed procedures are presented with their sources of errors and the precautions taken to minimise their effects. Then, the collected data is plotted to be part of a unique complete set of data. In this chapter, the data is not analysed. In effect, the following three chapters deal with their analysis.

Chapter.4 uses the data from the settling experiments to study the settlement of real drill-cuttings in water. Experimental settling speeds are compared to other experimental works and correlations. Drag coefficient correlations are also used to adapt the settling speed equation to different shapes and Reynolds numbers. General fluids dynamic phenomenons are described and a new correlation for the drag coefficient is revealed.

Chapter.5 deals with the validation of the settlement work. Here, all the experimental settling speeds are validated using a state-of-the-art CFD (Computational Fluids Dynamics) package. General principles for the solving of equations and the particle transport model are described. The procedures for the modelling exercise are presented in details. The different drag coefficient correlations (including the new one) are also introduced in the package to compare the different values. All the results (experimental, semi-theoretical and computational) are then analysed and interesting conclusions are drawn.

Chapter.6 shows the development of a new database including new correlations between the drilling parameters and the drill-cuttings size. After describing the general statistics used, it states the objectives and the needs for such a database. The modelled equations for the correlations are revealed. The Fortran 90 program written to support the database is presented and tested.

Chapter.7 finally summarises and concludes on the experimental and computational works. Suggestions and recommendations for further work are given at the very end of the document.

Chapter.2

DRILLING OPERATIONS AND ENVIRONMENTAL CONCERNS

2.1 INTRODUCTION

As stated in Chapter.1, the characteristics of cuttings need to be better studied, along with their correlations with the drilling parameters. This could only be achieved by studying the basics of drilling operations. Then, in order to put the data in a suitable way and understand more thoroughly the needs for such a work, the environmental concerns were researched.

Chapter.2 firstly presents the basic principles in drilling techniques. These are important to show how the cuttings are produced and how they should correlate with the drilling parameters. It then states the environmental concerns from drilling operations and how regulations and drilling muds evolved in the past decades. This gives an indication on what improvement in knowledge is required and in which format. Chapter.2 is aimed at presenting the basic principles needed to understand the needs for the present work and how it was conducted. This knowledge is also useful to understand the extent of applications of the present results as well as the scope for further work.

2.2 DRILLING TECHNIQUES

2.2.1 Drilling systems

2.2.1.1 Drilling a well

There are two major types of offshore drilling operations: exploration and development. Development operations consist in the drilling of multiple wells on a proved petroleum reserve. The offshore rigs used for exploration are usually mobile while the ones used for development are generally fixed. Offshore drilling rigs must be stable when they are drilling, mobile when required, economical and functional.

The major types of offshore rigs are shown in Figure 2.1. The offshore installations in Figure 2.1 are in the following order from left to right:

- tension leg platform;
- sub-sea collection manifold;
- concrete gravity platform;
- telecom tower to same scale;
- steel jacket platform;
- jack-up production platform with concrete sub-sea storage, and;
- not normally manned mono-pod platform.

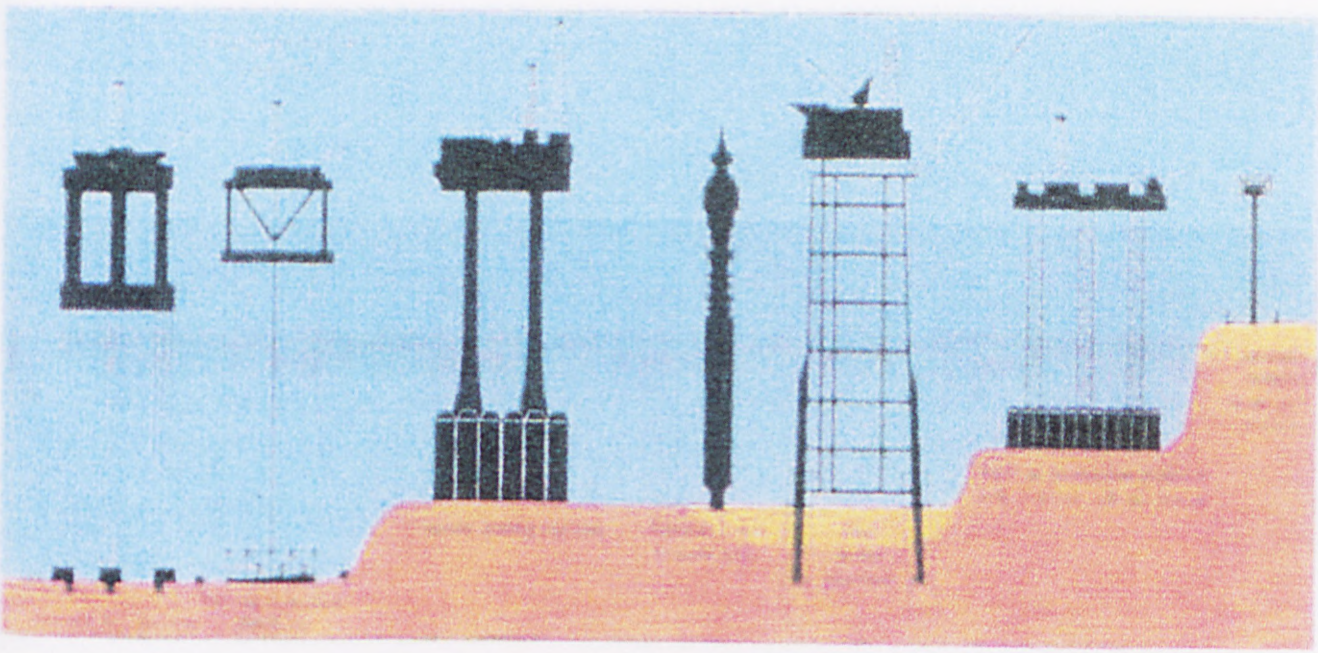


Figure 2.1: The different types of rigs (UKOOA 1997).

For exploration, there are two basic types of rigs employed: shallow water and deep water exploratory rigs. Three different types of shallow water exploratory rigs can be defined: barge rigs, jack-up rigs and semi-submersible rigs. Deepwater exploratory rigs can be divided into two groups: semi-submersible rigs and drill ship rig. In terms of data collection for this research, the major rigs are: semi-submersible, fixed platform, jack-up and a combination of two cited types.

A typical well is usually drilled in three stages. After the hole is begun at the surface (conductor hole, or 'spudded-in', the first stage of the well is drilled. This is called the 'surface hole'. Then the second stage of the hole may be drilled. This section is called the 'intermediate hole'. Then the final stage of the hole is drilled, called the 'production hole'. These concepts are described in more details later in this section. The drilling of a well is briefly summarised as to:

- get a conductor pipe going through underwater guides that are placed from just under the rig till the seabed;
- drill the first stage of the well which usually is an open hole (no cuttings return to the rig but are directly discharged on the seabed);
- for drilling, a drill bit is placed along with the BHA (Bottom Hole Assembly) at the bottom of a drill pipe (which is usually about 30 m);
- drilling fluids are pumped inside the drill pipe from just underneath the drilling floor to the bottom of the drill pipe (downhole);
- drilling fluids then circulate in the annular space between the drill-pipe and the borehole transporting the cuttings back the surface (this process was mentioned in Chapter.1);
- once the penetration length is slightly less than the length of the drill pipe, the drilling is stopped and another drill pipe is connected, then the drill starts again;
- when a section is finished or if a downhole tool has to be changed, the whole drill string (formed by the connected drill pipes) has to be pulled back up to the drilling floor and the connection process becomes disconnection process;
- then, the well is 'secured': a casing is run down and cemented, and;
- finally, another section can be started with the same basic procedures.

This document only describes the drilling part, and not the casing run or cementation. Figure 2.2 summarises the described stages of the overall process. Part.1 of Figure 2.2 shows the conductor hole being made. Then Part.2 deals with the drilling of the surface hole with the mud being pumped inside the drill pipe and circulating in the annular space. Part.3 and Part.4 represent the run of the casing and the cementation of the surface section. Part.5, 6, 7 and 8 show the same process again with the installation of a flat shoe at the bottom of the second casing. For the drilling of each different section, different drilling bit and drilling muds might be used. The different drilling muds and drilling bits are described in section 2.2.2 and 2.2.3 respectively.

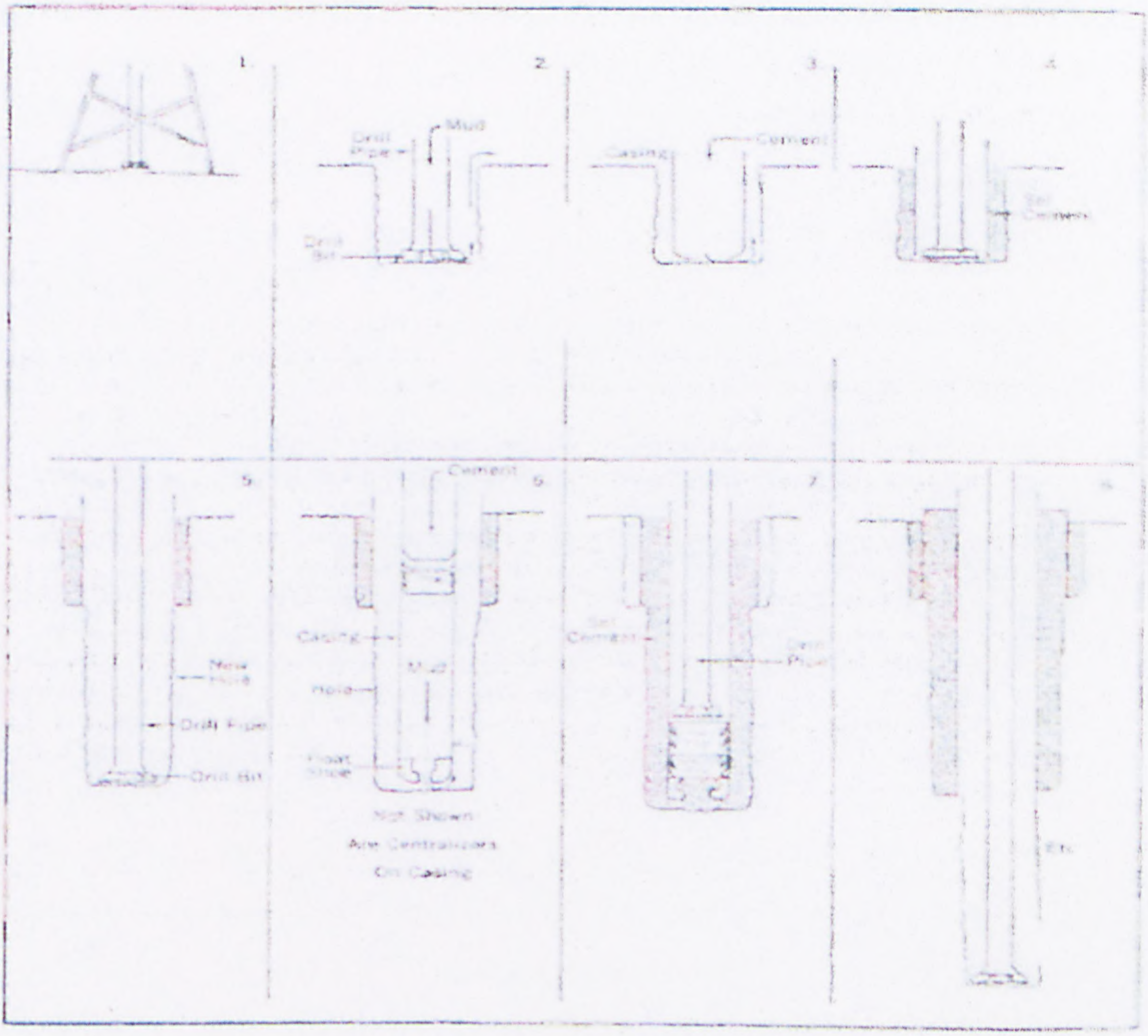


Figure 2.2: The different stages of drilling a well (Kennedy 1983).

A well will vary in the number of stages required for its completion depending on its location and the conditions encountered in the geological formations. For example, some wells do not require stage two, an intermediate hole. A brief description of each stage follows (and see Figure 2.3):

Stage 1 - the surface and conductor hole

After the conductor hole is made, the surface hole is the relatively large diameter (for example 36" and 26" conductors) well bore which is located immediately below the surface.

In the northern North Sea for example, soft sand is often encountered at that stage. On completion of the surface hole, casing is run into the well bore and cemented. This brings the surface hole under complete control and allows drilling to continue. At this stage, the cuttings are not brought back to the surface of the rig.

Stage 2 - the intermediate hole

A smaller diameter (for example 17 1/2" and 12 1/4") intermediate hole is then drilled. The casing (13 3/8'' and 9 5/8'' respectively) is run into the well bore and cemented. This brings the intermediate hole under complete control and allows drilling to continue. Several intermediate casing strings may be required for deep high pressure wells. However, an intermediate casing string is not always required, i.e. when loss of circulation is not anticipated in shallower formations, or when it is not necessary to seal off older producing zones. Generally, the volume of cuttings generated from these sections is high and the particles are very varied in shape and size.

Stage 3 - the production hole

Smaller in diameter (for example 8 1/2"), the production hole is then drilled to the target formation. Here, the volume of generated cuttings is small. Tests are then conducted to determine if the hydrocarbon presence is sufficient to justify the expense of running and cementing production casing into the hole. If found to be 'dry', the hole is plugged and abandoned.

Figure 2.3 shows the different sections for a vertical well. The principle is basically the same for deviated and horizontal wells. In Figure 2.3, the scribbled lines show the walls of the borehole, while the straight lines ending with a triangle represent the casing. The number beside each different section is the diameter of the borehole (the diameter of the casing is slightly smaller).

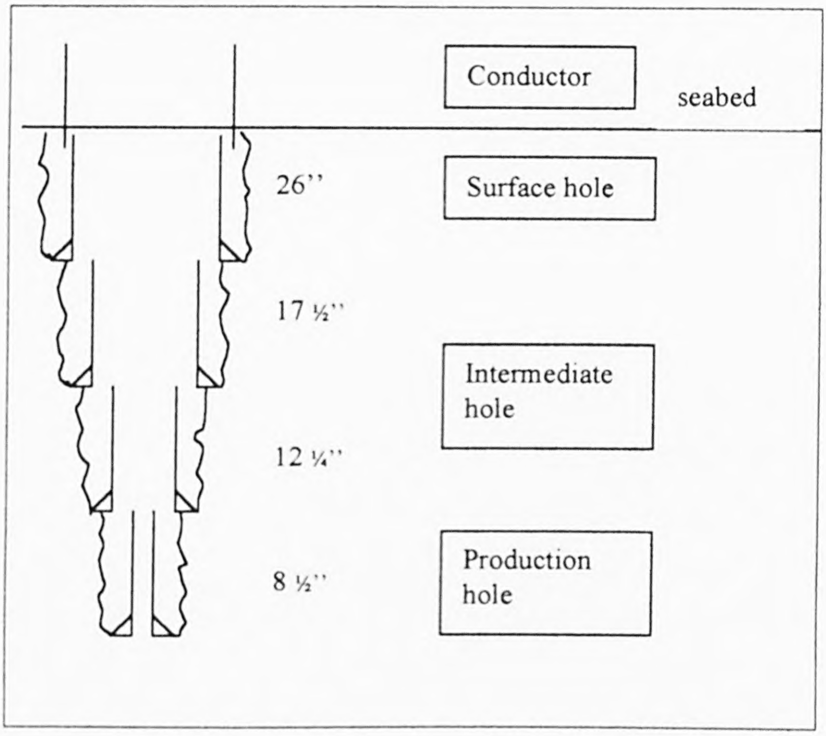


Figure 2.3: An example of the different well sections.

'Making a hole' is what modern rotary drilling operations are all about. However, there are a number of misconceptions that most people hold about the well bore that is actually produced. In the first place, the well bore is not drilled vertically straight, but in fact, it deviates considerably in a downward spiral. This deviation of the well bore is caused by the stratified nature of the subsurface formations that are penetrated by the bit. The formations influence the direction that the bit travels and if uncontrolled, may create serious down-hole problems in the well bore. The major problems created are well bore variations or irregularities called 'dog legs', 'key seats' and 'ledges', each of which impair movement of the drill stem in and out of the hole during drilling operations. These well bore deviations can also create a need for fishing operations, which are procedures used to remove unwanted objects from the well bore (i.e. stuck or broken-off drill stem).

Nowadays, there are two ways to drill a well: overbalanced and underbalanced. The first way keeps the hydrostatic pressure in the well higher than the formation pressure (overbalanced drilling). The second way keeps hydrostatic pressure in the well lower than the formation pressure (underbalanced drilling). Oil and gas wells are usually drilled through alternating layers of subsurface sedimentary formations which, in general become increasingly difficult to drill as penetration increases. As seen earlier in this section, the well bore becomes smaller as each section of the hole is drilled by either or a combination of two drilling methods. These are:

- 'straight hole', or;
- 'directional'.

There are times when limited surface space is available at a site, or when a formation cannot be reached from directly above or when well bore deviation is extreme. It then becomes desirable or necessary to deliberately deviate the direction in which the hole is being drilled in order to penetrate a specific target formation. This is called directional drilling. Nowadays. a very common procedure is to do what is called a 'sidetrack'. In this case, a 'window' is open on an existing well and another well is drilled in a new direction from that window. Figure 2.4 summarises these different features: vertical well, sidetrack and deviated or horizontal wells. There are other more complicated features such as multilateral wells where two or three of the basic features are combined.

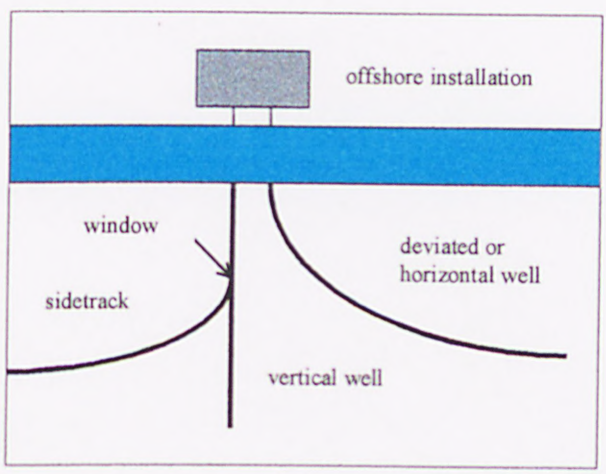


Figure 2.4: The different features of a well.

For this study, the three most important people amongst the drilling crew are: the mud engineer (or also called mudman), the mudlogger and the drilling supervisor (or/and the drilling superintendent). The mudlogger monitors data concerning the drilling of the well. Commonly, there is an update every 5 minutes on the mudlogger screens showing curves for ROP (Rate Of Penetration of the bit into the formation), RPM (Revolution of the drill string Per Minute) and other drilling parameters. The mudlogger also checks the geological properties of the rock formations. He/she takes a sample regularly from the shale shakers (described later in this section) and analyses it, looking at the density and the nature of the rock and the shape of the cutting. At the stage of the production hole, the geologist participates very closely in this exercise, trying to define the potential presence of oil or gas in the nearest layers of the formation. The mud engineer is assigned to the platform by the 'mud' company that will supply the components for the drilling fluid used in the circulating system during drilling operations. The drilling supervisor or/and drilling superintendent checks that the drilling operations are conducted properly and takes decisions whenever required.

2.2.1.2 The circulation system

On the offshore installations, there are many very complex systems to drill wells and produce oil and gas. For the purpose of this study, the most important system on board the rig is called the solids control system. It is located in the conditioning area. The purpose of this area is mainly to produce the drilling fluids with the required properties, to recover a maximum volume of drilling fluids after usage and to treat the solids coming back from downhole. This area is located on the rig under the drilling floor. It is where the drilling fluid is 'cleaned up' after it has been brought up out of the well bore. So, the drill-cuttings are generated at the bottom of the well, then come back to surface with the drilling muds. On the installation, the cuttings and the muds go through the solids control systems in the conditioning area. The remaining solid material after 'treatment' is then discharged. This overall system is called the circulation system and is shown in Figure 2.5. Each of the relevant items is described in the following paragraphs.

Firstly, the solids control system may include:

- mud-gas separator: is a device that removes large quantities of entrained gases that have entered the drilling fluid.
- shale shaker: is a device that removes large formation cuttings from the drilling fluid (see Figure 2.5).
- degasser: is a device that continuously removes entrained gases that have entered the drilling fluid. Muds can draw off fluids from the formation and gassy fluids are thus

mixed with the return mud. It is compulsory to clear gas from the mud, as the drop in density caused by this bubbling increases the likelyhood of a kick.

- desander: is a device that removes granular particles from the drilling fluid. They are hydrocyclones used either alone, or by sets of 2, 4, 6, or 8 cones coupled, or uncoupled, to the low or high pressure mixing circuit.
- desilter: is a device that removes the very fine particles from the drilling fluid. Desilters only differ from desanders by their increased separating capacity: they eliminate 95% of 28 microns and 50% of 13 microns particles (Moore 1986).

The desander and desilter are used for example when large quantities of sand are coming back up. Moreover, a centrifuge can be added to the conditioning process in order to get rid of fine cuttings (too fine to get trapped in the shale shakers). Any solid waste from the solid treatment apparatus is discharged through the same discharge chute, directly into the sea. Depending on the rig, the point of discharge can be located above or below the sea surface. For example, semi-submersibles usually discharge from above the sea surface while fixed platforms discharge from below the sea surface. Figure 2.5 shows a schematic layout of the circulation system.

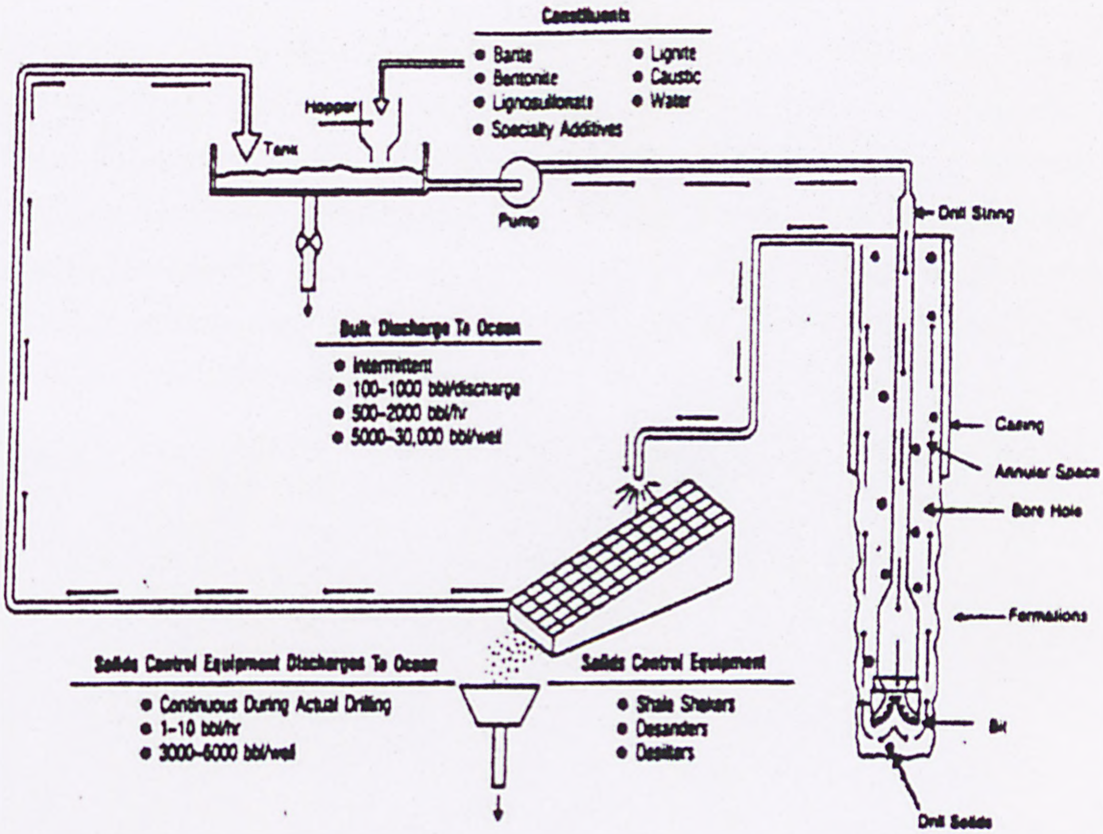


Figure 2.5: The circulation system of the drilling muds and cuttings (Gordon 1988).

When drilling, especially with oil based muds, minimising the amount of fluid discharged with the drilled cuttings is important for both economical and environmental reasons. Shale shakers have therefore been designed to remove cuttings from mud. They contain one or two racks with special screens, mounted on a frame by springs or rubber mounts. Mud is spread on the screen via a ditch. The vibration is obtained by an unbalanced shaft mounted on two bearing blocks integral with the screens. The speed of vibration has to be high enough to separate cuttings from mud and get the mud to pass through screens before further treatment and recirculation. Sometimes, there is the option of using secondary screens. These screens are used to dry the cuttings further when drilling with oil based muds or if dry solids are required to meet environmental restrictions.

Dual shale shakers were developed a few years ago. Their principle is the same as the conventional shaker, with two superimposed horizontal screens. The upper screen is of the usual size (from 8x8 to 30x30 – that means, for example, that there are 8 metal wires per inch, giving a mesh with a diameter of 2.464 mm). The lower is from 50x50 (0.279 mm) to 230x230 mesh (0.117 mm). Special orders can be made: 40x40 (0.381 mm) to 100x100 (0.140 mm) for the upper screen and 325x325 to 330x330 for the lower screen (Total year unknown). The top screens are designed to scalp off large volumes of solids such as occur during fast top hole drilling. Their function is to remove large particles and protect the lower screen from physical damage. They should be selected such that the majority of fluid passes through the first third of the screen (see Figure 2.6).

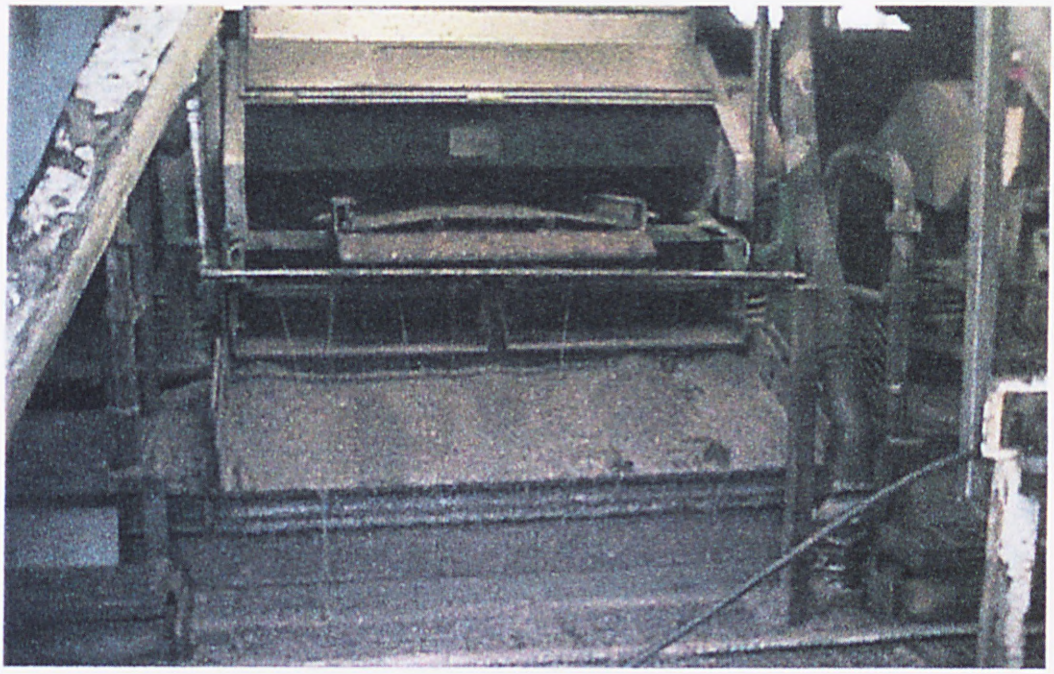


Figure 2.6: Shale shakers separating mud and cuttings.

Hence, the cuttings size distribution depends on the equipment used in the solids control system. Some of the finest screens and secondary treatments (like desilter) can even trap fine particles contained within the muds (i.e. barite in WBM and OBM). The wastes discharged through the caisson chute therefore contains drill-cuttings of every size as well as fine particles from the drilling muds.

2.2.2 Drilling muds

2.2.2.1 Background

This section briefly describes the properties and functions of the drilling muds. The drilling fluid is a mixture of various components which can include: water, oil, clay, chemical additives, gas, air, mist, foam or soap with its composition determined by the down-hole conditions and the types of formations being drilled. There are three basic types of drilling fluid: water based (WBM), oil based (OBM) and air or gas based - the most commonly used being WBM. Usually, seawater or light WBM is used for the surface hole, then WBM again for the intermediate hole and OBM for the smaller sections.

Historically, WBM have been extensively used in the North Sea; however, drilling certain formations with WBM can prove difficult primarily due to hole instability caused by the swelling of water-absorbing rock. Problems of this type can be greatly alleviated by using mud suspended in an oil-base rather than water. Oil-based drilling mud has other advantages over WBM, notably it provides better lubrication, and it has also been found that significant increases in drilling progress can be achieved by the use of OBM. OBM are used for a variety of applications where fluid stability and inhibition are necessary, such as high-temperature wells, deep holes, and where sticking and hole stabilisation is a problem.

These advantages are brought to the fore in the North Sea, particularly in the deep water Northern Fields, where the very high investment required for construction of platforms dictates drilling as many wells from one platform as possible.

According to World Oil 1996, ten distinct drilling fluid systems can be defined, with seven being water-based, others being oil- and synthetic-based systems. The main water-based drilling fluid systems are: non-dispersed, dispersed, calcium treated, polymer, low solids, saltwater systems and workover. For example, fresh water bentonite mud is relatively inexpensive drilling mud which is used widely in drilling operations. Bentonite is added to bring up the viscosity of the mud. The main mud parameters are maintained by careful balancing of clay and lignosulfate additions.

After the base of the mud has been selected as being water, oil or gas, additives are used to change the properties of the muds. For example, gypsum is sometimes added to the mud

when large amounts of active clay must be drilled. Moreover, OBM consist of two types of systems: invert emulsion muds and oil-based muds. All oil systems require higher additional gelling agents for viscosity. For example barite is added to add weight to the mud.
Most drilling muds are in aqueous suspension, however in the North Sea, oil is frequently used to replace the water. Oil is often the option for its greater suitability for drilling through rock strata that contain shales, clay stones and salts which either soften and swell or dissolve in aqueous solution causing sticking of the drill strings or collapse of the well. A high majority of the samples presented in Chapter.3 came from WBM drilled wells.

2.2.2.2 Properties

Drilling muds are a very important component of the drilling system and their properties are monitored very regularly and carefully. The main properties measured for the drilling muds are: density, apparent and plastic viscosities, yield point, gel strength and filtration properties. They all depend, of course, on the type of mud used by the oil company. A brief summary of each of these properties is necessary to be able to understand the physical processes that will affect the behaviour of these fluids. Firstly, the density is defined as weight per unit volume and is expressed in pounds per gallon (lb/gal), pounds per cubic foot (lb/ft^3) or in kilograms per cubic metre (kg/m^3). The yield point (lbs/100 ft^2) is the measurement of the electrochemical or attractive forces in the mud. The apparent viscosity is defined as the ability of a fluid to flow (Chiligarian 1981). The more viscous the fluid, the greater the resistance to flow. The plastic viscosity is the shearing stress in excess of yield point that will induce a unit rate of shear. Plastic viscosity is that part of the flow resistance caused by mechanical friction. This friction occurs between:

- solids in the mud;
- solids and liquids that surround them;
- the shearing of the liquid itself.

The standard unit of viscosity is the poise, but the unit employed in mud viscometry is the centipoise (one-hundredth of a poise). The ability of the mud to hold drill cuttings in suspension under static conditions (this assumption is very important) will define the gel strength. Units for gel strength (used in the petroleum industry) are pounds per hundred feet. Finally, the filtration properties can be summarised as the ability of the mud to seal permeable formations with a thin, low permeability filter-cake. They are the fluid loss (ml) and the cake thickness (inches)

The mudweight or specific gravity is a key-factor in the control of bottom hole pressures and hole stability. Increase of mudweights, however, causes a considerable reduction in penetration rate and a significant increase in friction losses (viscosity). The mudweight is generally expressed as specific gravity (SG) or pounds per gallon (ppg). The viscosity of the mud is very important for the optimisation of various different mud functions. The viscosity is measured using two different instruments: the Marsh funnel and the Fann viscometer. Gel values are a measure of the build-up of gel structures in the mud under static conditions. They are measured after 10 seconds and 10 minutes of static build-up of the mud. A reasonable 10 second gel is essential to prevent immediate settling of solids when circulation is stopped. The next table (Table 2.1) gives an example of a WBM properties for different depths in an oil well in the Northern North Sea.

Depth (m)	Temp (°F)	Density (SG)	Fun Vis (sec/qt)	Rheology at 120degF PV cP	YP lbs/100ft2	GELS	pH	Sand	Oil (% by vol)	Water (% by vol)
884	68	1.090	51	11	38	18.0/ 20.0	9.8	0.6		95
2866	127	1.539	77	35	43	18.0/ 34.0	11.7	0.4		75
2960	68	1.620	83	33	50	29.0/ 52.0	11.8	0.25	0.2	73
3210	77	1.620	73	31	36	23.0/ 51.0	11.9	0.5	0.1	75
3554	124	1.620	60	28	29	25.0/ 49.0	11.8	0.25	0.1	72.9

Table 2.1: An example of WBM properties for different depths in an oil well in the Northern North Sea.

2.2.2.3 Functions

The properties of the drilling muds are closely related to their functions. They have to be well-balanced to optimise the efficiency of the mud. Although originally designed to bring the drilled cuttings from the bottom of the hole to surface mud now serves at least twelve important functions in modern drilling operations (Moore 1986 and Chiligarian 1981).

Mud assists in making hole by:

- removal of cuttings
- cooling and lubrication of bit and drillstring
- power transmission to bit nozzles or turbines
- Mud assists in hole preservation by:
- support and stabilisation of borehole wall
- containment of formation fluids/gas

It also:

- supports the weight of pipe and casing
- serves as a medium for formation logging
- prevents hole wash outs due to turbulence or dissolution
- must be compatible with drilled formations and encountered formation fluids/gas

It must not:

- corrode bit, drillstring/casing and surface facilities
- impair productivity of producing horizon
- pollute the environment.

The relationships between mud properties and the drilling conditions are very complex and are a two-way process. For example, the geological formations influence the properties required for the mud; and the mud properties influence some of the drilling parameters like ROP. The table below (Table 2.2) shows the relationship between some of the properties with the effect on the ROP, and also the chemicals added to reach the required value for the property (Basic Drilling year unknown). Some chemicals (e.g. bentonite, lignites, lime, potassium chloride, biopolymers...etc) are used to either increase the pH, the viscosity, the density, the gel values… etc. This table is not exhaustive and there are exceptions to the cases presented.

Function of the mud	Relevant Property	Effect of property on ROP	Chemicals for control
Confines formation pressures	Mud density	Increased mud density decreases ROP	Raise by adding BARYTES Lower by adding WATER (but check viscosity)
Carries out cuttings	a.Viscosity	Increased mud viscosity decreases ROP	Raise by adding BENTONITE Lower by adding WATER (check density) or THINNER
	b.Bingham yield point c.Gel strength	Increase yield point and gel strength decreases ROP	Raise by adding BENTONITE Lower by adding THINNER
Protects and supports bore-hole wall by the formation of an impermeable mudcake which also minimise contamination	a.Fluid loss	Decreased fluid loss slightly decreases ROP	Lower by adding THINNER
	b.Solids content	Increase solids content decreases ROP	Raise by adding WATER Keep as low as possible by continuous removal of unwanted clay, silt, sand and cuttings
Lubricates and cools bit and drill string	Water content	Increased water content increases ROP	

Table 2.2: Functions and properties of oil well drilling fluids (Basic Drilling year unknown).

The knowledge of the drilling parameters is necessary to understand their connections with the size of drill-cuttings. The chosen parameters for the present study are described in section 6.2.1. Not all the information presented in Table 2.2 was used for the present study. However, some recommendations for further work (section 7.3.1) and the analysis of the disaggregation tests (section 3.3.2.d) need an advanced knowledge of the mud properties.

2.2.3 Drill-cuttings

2.2.3.1 Background

Drill-cuttings are small chips or cuttings of rock resulting from the penetration of the drilling bit into the geological formations. Their size ranges from fine sand to gravel. Their shape or sphericity (e.g. their similarity to a perfect sphere) varies enormously with the conditions under which the cuttings have been drilled and the type of rock (see Figure 2.7).

Figure 2.7: Differently shaped cuttings.

The nature of the rock depends on the geological formations being drilled. The type of rock and the depth dictates the density of the cutting. The three main characteristics (i.e. size, shape and density) influence directly the settling speed of the particle and therefore of the drilling wastes into the sea. Here, the settling speed is defined as the terminal velocity of the cutting in a medium under static conditions. None of these characteristics are well-known in the oil industry but remain a key factor influencing the dispersion of the wastes into the sea. They are also very important for predicting the efficiency of drilling muds for hole-cleaning or designing the solid waste treatment on board for example. Therefore, in this study, the characteristics of cuttings are better defined and analysed to form a database. In this document, the size of the cutting is taken as the 'sieve diameter', which in most cases is equivalent to the longest diameter. In the case of very flat particles, the sieve diameter can also be the shortest depending on the orientation of the particle when it went through the sieve mesh. Shape can be simply defined by three main categories: round, angular and flat. The density of the particle is defined in $kg.m^{-3}$.

2.2.3.2 Drilling bits

From what has been described so far, it can be assumed that the cuttings characteristics are going to be largely influenced by the way the cuttings have been drilled. For example, one of the major factor of influence will be the drilling bit. The choice of the bit is critical and the following parameters are generally taken into consideration:

- service life;
- efficiency;
- time necessary for a trip, and;
- nature of the geological formation.

One commonly used drilling bit is the rock bit for example. For each different geological formation, if rock bits (also called roller bits) are chosen they should selected as follows:

- for shale soft limestone clay or unconsolidated formations: bits with long teeth, well spaced.
- for soft formations with hard intercalation: bits with shorter teeth
- for medium hard formation: hard limestone/dolomite/hard sands: bits with shorter, stronger teeth closely spaced.
- for hard formation like hard limestone/quartz: bit with very short and numerous teeth.

The bit, attached at the end of the drill string, is generally from the three typical types: 'rock bits', 'insert bits' and PDC (Polycrystalline Diamond Compact) bits. Devereux (1998) defines the conditions in which each type of bits is generally used. According to him, mill tooth bits (called 'tooth bits' or 'rock bits') are most useful in soft formations, usually the top sections of the hole. One large bit may drill top hole for several wells. Mill tooth bits are also used in formations that contain harder breakage due to shock loading. Certain strong, 'elastic' shales can be drilled better with a mill tooth bit than a PDC or insert bit. Figure 2.8 represents an example of a mill tooth bit.

Figure 2.8: An example of a mill tooth bit (Courtesy of Baker Hughes).

Figure 2.9: An example of an insert bits (Courtesy of Baker Hughes).

Insert bits have teeth made of tungsten carbide (see Figure 2.9) and today, their cutters can be very long lasting. These bits are more expensive than mill tooth bits using the same bearing structure but are far more durable. They are certainly more popular in medium, hard and very hard formations.

PDC bits use a thin wafer of diamond mounted on a stud (see Figure 2.10). They are good in plastic formations (e.g. medium shales and salt) and can give fast ROP over long intervals. Early PDC bits used in WBM tend to encounter problems but better WBM technology seems to have overcome this. However, it is still very common to use PDC bits with SBM. PDC are usually not suitable for formations containing hard nodules for example.

Figure 2.10: An example of a PDC bits (Courtesy of Baker Hughes).

All bits have passages that allow drilling fluid to pass through and sweep away the rock cuttings as the bit drills deeper. The high-velocity jetting action allows the drilling fluid to penetrate the fractures on the hole bottom and helps release rock cuttings generated by the bit teeth. Drilling fluid and rock cuttings rise in the annulus between the drillcollar and hole wall, and then in the annulus between the drillpipe and hole or casing wall. The ability to transport cuttings up the annulus depends partly on the annular velocity of the drilling fluid.

It also depends partially on the mud properties and drill-cuttings characteristics, which determine the carrying capacity characteristics. Under static conditions, cuttings fall or slip faster through a 'thin' fluid than through a 'thick' viscous fluid. Obviously in order to transport cuttings to the surface, the fluid velocity must be greater than the cuttings slip velocity.

On another hand, by looking at the previous images of bits (see Figure 2.8, 2.9 and 2.10), it seems obvious that different cuttings (in terms of size and shape) are expected to be produced by these drilling bits.

2.2.3.3 Other information

The characteristics of the rock, even from the same lithology, differ from one stratigraphy to another. For example, a clay formation might be harder and denser in a deeper stratigraphy. Cuttings from the North Sea oil fields are often shale and sandstone. Individual particles may range in size from few microns to one or two centimetres. Because of their material properties and the manner in which they are produced, these particles are generally asymetric and often have a flake structure (diskoid). One example is that PDC bits give a very specific type of drill-cuttings from certain formations: sometimes 'banana shaped' (see Figure 2.11 on the left hand side) and always with scorings (see Figure 2.11).

Figure 2.11: Cuttings drilled with PDC bits.

The type of drilling mud used also plays a significant role in determining the morphology of the cuttings, first through its influence on the size of particles cut from the strata and second through its stickiness, which helps agglomeration of the particles (McFarlane *et al* 1991). Moreover, the speed at which the bit rotates (RPM) and the speed at which it penetrates the formation (ROP) must also have an influence. Most of the intuitive suppositions made in this section are verified in Chapter.6. There, the characteristics of the drill-cuttings and the influence of the drilling parameters on the characteristics are analysed.

Another useful information is the temperature of the mud and cuttings. When the material arrives after a long trip from the bottom hole, its temperature can be high (e.g. a common temperature would be between 50 and 70 degrees Celsius). Depending on the composition of the mud, some chemical reaction or thermal reaction might happen when the discharge enters a 10 degree Celsius seawater. It might also be in favour of a better disaggregation of the cuttings during their journey back to the rig (disaggregation phenomenon is dealt with in section 3.3.2).

Moreover, on offshore rigs, the oil content on cutttings is regularly monitored to estimate the mud loss per day and to check if environmental regulations are respected. The volume of drilling wastes discharged and the rate at which it is discharged are key factors to predict the impact on the environment. On some offshore installations, a 'cuttings flow meter' has been installed. It measures with accuracy the amount of material discharged from the shale shakers. This is very useful information as it allows to input the volume of material discharged in simulations. It also enables the drilling engineer to visualise if the hole-cleaning process is as predicted and to anticipate any relevant problem.

2.3 ENVIRONMENTAL CONCERNS

2.3.1 Background

In the previous sections, the drilling techniques were presented. This description shows that chemicals used in the drilling muds are discharged along with the drill-cuttings. Most of the time, after separation with the mud, the remaining material is directly discharged into the sea. This method raised the problem of marine pollution. As a result of these environmental concerns, drilling muds and regulations evolved. These evolutions are presented in the following sections. The impacts of the environment and their extent are also described in these sections.

First of all, wastes, discharges and emissions can conveniently be split into three major categories: solid wastes, aqueous discharges and atmospheric emissions. For each of these categories, there are what can be considered as major sources and minor sources. Some of the major and minor sources might either have a significant environmental effect or an insignificant effect (Sneddon 1994). Here, the debate is long on the meaning of the significance of environmental detriment and the value of environmental resources. What is a significant loss in the environment? How much is acceptable to lose? How much can we spend not to lose any? The list of questions could be long and the philosophical debate interesting but endless and subjective.

Oil and gas exploration and production operations can induce potential environmental impacts which can cause conflict between the fishing and oil industries. These impacts which have been studied at numerous geographic locations, include the routine disposal and possible accidental release of various contaminants (primarily sediments, hydrocarbons and metal traces). Potential impacts depend very much upon the time of the year that operations take place. This is because the physical oceanographic processes that affect dispersion as well as the susceptibility and vulnerability of marine organisms change seasonally (Gordon, 1988). Input of material into the sea associated with offshore drilling and production include:

- accidental spillage;
- discharge of drill-cuttings and drilling muds;
- discharge of production water.

Discharged drill-cuttings and drilling muds are, by far, the greatest source of oil finding its way to the seabed from drilling operations (Sneddon 1994, Brandsma 1994, Gordon *et al* 1992, Gordon *et al* 1995 and Minton 1993). The oil on cuttings come from the drilling muds that were described in the previous sections. Accidental oil spills contribute relatively small quantities of oil to the overall total discharged to the North Sea. Although spills are frequent (250 recorded by the UK Department of Energy in 1987 alone) they are usually less than one tonne. The spills generally result in a sheen in the water around platforms and can be detected by aerial surveillance.

According to Sneddon (1994), of all the solid wastes generated in exploration and production activities, by far the greatest quantity is from drill cuttings which amounted to an estimated 164,000 tonnes in 1993 in the UKCS (United Kingdom Continental Shelf). Following this and largely associated with cuttings are the weighting agents used in drilling muds which in the UKCS in 1993 amounted to over 151,511 tonnes of material. A summary of solid waste discharges for 1993 is given in table 2.3.

Material	1993 Discharges in tonnes (UKCS)
Cuttings	164000
Drilling chemicals	151511
Production chemicals	3268
Total	318779

Table 2.3: Summary of solid waste discharged into the North Sea in the UKCS from exploration and production activities in 1993 (Sneddon 1994).

Once cuttings are discharged into the sea, they behave differently according to the conditions in the marine environment and the particles characteristics. In the strong currents of the shallower southern North Sea, as in many other parts of the world, they rapidly disperse. This allows any remaining mud traces to spread over a large surface of the seabed and to often biodegrade naturally. But in the much deeper waters of the central and northern North Sea where seabed currents are weaker, off both Britain and Norway, the fine particles gradually accumulate under offshore installations forming 'cuttings piles' which can reach more than 10 metres. The content of drilling muds has long been controlled by regulations; and the evolution of its content as well as that of the regulations has been dictated by environmental concerns. Scientific research has been and is still very active to find better muds wich better respect the environment and also to find better ways of assessing the impacts of drilling wastes on the marine fauna and flora.

2.3.2 Evolution of the drilling muds

Due to environmental concerns (and also to a technically demanding systems), drilling muds have evolved a great deal in the past decades. For every new development, engineers and scientists need to keep in mind the technical and environmental aspects. For example, for difficult wells, operators need to add lubrication to the mud to stop the drill from sticking. In the early days, the only available lubricant was diesel, which was banned in 1984 for environmental reasons. Diesel has been replaced firstly by a more refined Oil Based Mud (OBM). Then, Mineral OBM and Low Tox OBM appeared. Over time lighter and lighter lubricants have been used to limit environmental risks. Then, Pseudo OBM (POBM) was used but the name would not correspond to the public's opinion of a more environmental friendly drilling mud. So the name was changed to Synthetic Based Mud (SBM). These new mud formulations which contain less base oil may lead to reduced levels of oil on cuttings (Davies 1987). However, according to the general opinion, the name is different but the product is the same. It should theoretically have less impact on the seabed environment. In practice, however, the switch to the so-called 'low-toxicity' drilling muds made little difference (Kingston 1997).

The lubricators in SBM are 'synthesised' from products such as ethylene (SBM have a very specific smell). They basically contain carbon, hydrogen and oxygen atoms in different configurations, selected for their low toxicity and ability to biodegrade. Research has now shown that synthetic muds are not breaking down naturally in seawater as quickly as expected. In a further move to minimise impacts, operators in the UK are phasing out discharging cuttings contaminated with synthetic muds by the end of the year 2000. In the PARCOM (Paris Commission) decision 92/2 adopted in 1992, it is stated that the content of Low-Tox OBM on cuttings should be less than 1%. The oil on cuttings for POBM is commonly less than 10%. This threshold although never stated in any legal regulation is self-controlled by costs (Moore 1998).

The problem of cuttings disposal alternatives is a very actual and interesting subject. UKOOA (United Kingdom Oil Operators Association) launched the ‘cuttings initiative’. The two main activities of this initiative are to assess the best option for cuttings disposal and cuttings pile removal. One alternative for the cuttings disposal is to re-inject them into the wells. But this method is not always possible. Another disposal alternative is 'cuttings to shore'. Some companies like Shell are practising this method whenever feasible and have developed plants in England to treat the cuttings once onshore. The new ways of working will involve a commitment of some £50 million a year in extra costs by the offshore industry (UKOOA 1998).

2.3.3 Adequate regulations

As stated in the previous section, the drilling muds and disposal methods evolved as result of the operators effort to minimise pollution. However, at the same time, regulations for the discharge of the muds and cuttings are also evolving. As Littleton (1986) stated, the evolution of the regulations will increasingly complicate offshore mud disposal. Progressively, the government asks the operators to assess the environmental impacts and their extent. The carrying out of an environmental impact assessment for certain types of project was required throughout the European Union by virtue of the 1985 Council Directive "The assessment of the effects of certain public and private projects on the environment" (85/337/EEC). The Offshore Petroleum Production and Pipe-lines (Assessment of Environmental Effects Regulations) 1998 have been implemented for wells, pipelines and developments on the UKCS by Guidelines. These guidelines explain how to apply the Directive to different projects. The 1998 Regulations are in relation to measures relating to the requirement for an assessment of the impact on the environment of projects likely to have significant effects on the environment (DTI February 1998). The 1985 Directive has since been amended by Council Directive 97/11/EC of March 1997. These Regulations do not give effect to the amending directive but two of its thresholds have been selected as criteria as to when an environmental impact assessment (EIA) is mandatory.

Regulations were issued to implement fully the requirements of the 1997 Directive. The purpose of the Regulations is to allow the Secretary of State for Trade and Industry to take into account environmental information before making decisions whether or not to authorise various offshore projects. To achieve this, the Regulations require any Licensees (anyone applying for a License) who wish to undertake a project must first prepare an EIA having made an assessment of the impact that the project would have on the environment (DTI February 1998). The EIA should include 'an estimate by type and quantity of expected residues and emissions of any kind resulting from the operation of the proposed project [...]; a description of the likely significant effects of the proposed project on the environment resulting from the existence of the project, the use of natural resources, the emission of pollutants, the creation of nuisances and the elimination of waste, together with a description of the forecasting methods used to assess the effects on the environment; a description of the measures envisaged to prevent, reduce and, where possible, offset any significant adverse effects on the environment.' (DTI April 1998).

2.3.4 Environmental impacts

2.3.4.1 Impacts on fauna and flora

So, what are the environmental impacts from discharging operational wastes? According to Ferbrache (1983), the possible detrimental effects from the discharge of drilling wastes on the marine environment can be summarised as follows:

- physical smothering of benthic epifauna and infauna;
- alteration of sediment chemistry and texture making it unsuitable for certain species e.g. interference with burrow construction and feeding;
- alteration of sediment chemistry and texture such that the settlement of benthic larvae is affected;
- introduction of substances (not necessarily directly toxic) which would impose a heavy biological or chemical oxygen demand on the sediments;
- introduction of toxic substances such as heavy metals;
- introduction of material which might have an indirect effect on communities by altering behavioural patterns, decreasing resistance, reducing fecundity etc.

The lack of oxygen in the accumulations means bio-degradation is much slower, so the cuttings still contain mud residues which have not thoroughly broken down over time as first thought.

2.3.4.2 Measuring the impacts

Environmental impacts are measured by monitoring changes, if any, in the biota (i.e. the 'living' community) of the receiving environment and relating this to physical and chemical measurements of possible pollutants. In order to achieve this it is desirable that the biota remains in the vicinity of the source of pollution. Free swimming forms (e.g. fish and crustacea) are able to avoid chronic pollution and do not always provide the best means of detecting point sources of contamination. Direct measurement of chemical contaminants in the surrounding water is also not always effective since current action and dilution factors quickly reduce concentrations of pollutants below that which may be accurately measured. Furthermore, intermittent discharges would require continuous monitoring which is usually impractical. It is for these reasons that the greatest monitoring efforts have been focused on the seabed and its biota (Kingston 1997). After discharge, pollutants finally settle down on the seabed and accumulate in the sediments. The dependence of the organisms that live in the sediment on particulate food sources make them vulnerable to such contaminant accumulation and therefore more likely to reflect deterious effects early on. Since most of these organisms are sedentary, they also act as biological integrators 'recording' intermittent pollution effects over the life of the offshore development. In order to know more about the impacts on the living organisms on the seabed, it is vital to know:

- what is discharged (i.e. mud properties and drill-cuttings characteristics);
- how much is discharged;
- the conditions of the discharge.

The present study will certainly help further work on those topics. Moreover, the previously presented ‘cuttings flow meter’ gives the volume of discharged material with a good accuracy. This certainly helps in assessing the environmental impacts and in improving the dispersion models.

For the past decades, oil companies amended seabed surveys to monitor the environmental impacts of their operations. It soon became obvious that the major effects on the environment were going to be very localised. Sampling strategy switched from a wide grid approach to transects which originated very close to the platforms following the line of prevailing bottom currents. The most common approach currently used is to sample the seabed by 0.1m2 area grab sampler at stations placed 200, 500, 800, 1200, 2500 and 5000m from the installation. The sediments are sieved through either 0.5 or 1.0mm mesh aperture sieves and the retained material analysed back at the laboratory. Samples for physical and chemical analysis are taken at the same time (Kingston 1987). But only few studies had sampling stations within the 500m prohibited zone that had been set up to protect the installations.

During a seabed survey in March 1997 on the Scotia II with a team from the Marine Labs (an office from Scottish Office for Agriculture and Fisheries), it was observed that the results of a seabed survey depend on:

- when (in the year and the day) the survey is conducted;
- the number and locations of the stations and the whole planning of the survey;
- the reliability and knowledge of the scientific crew;
- the experience and accuracy of the boat crew, and;
- the equipment on board and the standard of the boat itself.

The aim of the seabed survey conducted in March in the Northern North Sea was to monitor the concentrations of hydrocarbons in the upper layer of sediments and the recovery of some fish species after the Braer oil spill in 1992. The aim as far as the author is concerned was to learn the techniques of seabed survey, grab and core sampling. It shows the author in which extent seabed surveys can be trust when dealing with the validation of dispersion models.

2.3.4.3 Common results

As oil contamination spreads outwards from the cuttings piles on the seabed, the concentration of hydrocarbons in the sediment decreases. Levels of oil that have a detectable effect on the benthos (50-60ppm) are reached for most installations in the range of 750 to 1000m from the point of discharge. Very high concentrations, usually between 1000 and 10000 times 'background' are apparent close to the platform with a steep downward gradient between 500 and 1000m from the installations. This is typical for most North Sea oil developments (Kingston 1997).

As can be observed from what is previously stated, the interpretation of any survey on the marine environment is very complex and subjective. For example, it remains difficult to interpret the impacts of oil-induced mortality on early life stages of finfish and invertebrate resources because of large and variable natural mortality (Gordon 1988). Davies *et al* (1984) evaluated the environmental effects of oil-based mud on drilling cuttings using all available data from monitoring around North Sea platforms (see Table 2.4).

Maximum extent within range	**Biology**	**Chemistry**
0 - 500m	Impoverished and highly modified benthic community (beneath and very close to the platform the seabed can consist of cuttings with no benthic fauna)	Hydrocarbon levels
200 - 2000m	Transition zone in benthic diversity community structure	Hydrocarbon levels above background
800 - 4000m	No benthic effects detected	Hydrocarbon levels back to background
after 4000m	No benthic effects	No elevation of hydrocarbons

Table 2.4: The zones of effects of oil-based drilling mud cuttings based upon a wide range of surveys around the North sea oilfields (modified from Davies *et al* 1984).

Other evidence of effects from discharge of drilling wastes is fish tainting and the sensitivity of sea scallops to bentonite (Gordon *et al* 1992).

The writing of an EIA is an exercise to anticipate and minimise the impacts of drilling operations (amongst numerous other operations). The knowledge presented above combined with existing dispersion models (see section 1.2.1.2) helps achieving the requirements of the EIA. Therefore, in order to help in the design of seabed surveys, to conduct EIA and to understand the dispersion of drilling wastes, a better knowledge is needed in settlement properties and discharge characteristics.

2.4 SUMMARY

In Chapter.2, the basic knowledge of drilling techniques was acquired. Environmental concerns became more and more significant for operators and government. Pollution comes from both OBM and WBM cuttings and new regulations have been put in place. These regulations state certain thresholds for the oil on cuttings for example. Moreover, since the 30th of April 1998, EIA is mandatory but must also be made public for a length of time at least equivalent of four weeks. Anyone can get a copy of the document for a small fee of £2.00 (this is to cover the printing costs) (DTI April 1998). The requirements for the EIA have been described, as well as the general methodology of computational models used to help the writing of such a document. These models have been developed in several countries and are widely used. They all work on the same basis, require the same input and give similar output data. But, they all 'force' the consultants to use guesstimates for the cuttings characteristics. They also solve equations which might not always be appropriate to irregularly shaped particles like drill-cuttings.

Environmental engineering was described as becoming part of the offshore operations. Regulations and drilling muds were shown to evolve as a result of environmental concerns. With these basic principles, it is now easy to understand that drill-cuttings discharge has been an important matter for the past decades. Discharge dispersion models are sensitive, amongst all variables, to the cuttings size and settlement properties of the particles. The next chapters of this document deal with these two different subjects.

Chapter.3
CHARACTERISATION OF DRILL-CUTTINGS

3.1 INTRODUCTION

Chapter.3 deals with the assessment of the characteristics and aquatic settling properties of drill-cuttings. Firstly, the collection of data and samples is presented. Chapter.3 then describes the detailed procedures for the experiments conducted. The sources of errors and precautions taken during the experiments are also discussed. Size distributions and settling speed curves are then plotted for further analysis. This chapter does not present the analysis of the data which is the main objective of the following chapters.

3.1.1 General methodology

In order to characterise drill-cuttings, offshore samples needed to be collected. Corresponding drilling parameters were also necessary for the study of correlations. The aim of the collection of data and samples was to obtain all the drilling information for each sample provided. Once the samples arrived in the laboratory, the sieve analysis and the shape assessment could be conducted. Then, the settling could also be measured in a water tank. As a result of the experiments, the necessary information could be obtained about drill-cuttings.

The data was collected in several ways:

- through an offshore survey;
- from sieving and settling experiments, and;
- from obtaining sieve data from a Norwegian company.

Firstly, in order to collect samples and corresponding drilling parameters, an offshore survey was conducted. The samples were part of the offshore survey requirements and were sent regularly from the participating offshore installations. The survey was in fact designed on an offshore installation: the Galaxy I. This rig was a jack-up in the Central North Sea and was operated by Elf Exploration plc. The best design was achieved thanks to the kind help of the drilling supervisor, the mudloggers and the geologists. The objectives of this survey were to:

- get samples to be collected by the mudlogger each time there was a significant change in one of the drilling parameters of the questionnaire;
- collect the drilling parameters under which the sample has been drilled;
- get basic information about the drill-cuttings characteristics, and;
- keep the collected information consistent.

The survey was first tested on the Galaxy I to make sure that the relevant data was asked but also to ensure that it would fit into the routine of the mudloggers. The latter point was very important for two reasons:

- if it had been too different from their routine, the mudlogger would not have taken time to do it or will not do it properly, and;

- if it had been too stringent, then the operators would have refused to give the permission as they would not have wanted to increase the load work of the mudloggers.

The general methodology behind the whole collection of data is shown in Figure 3.1.

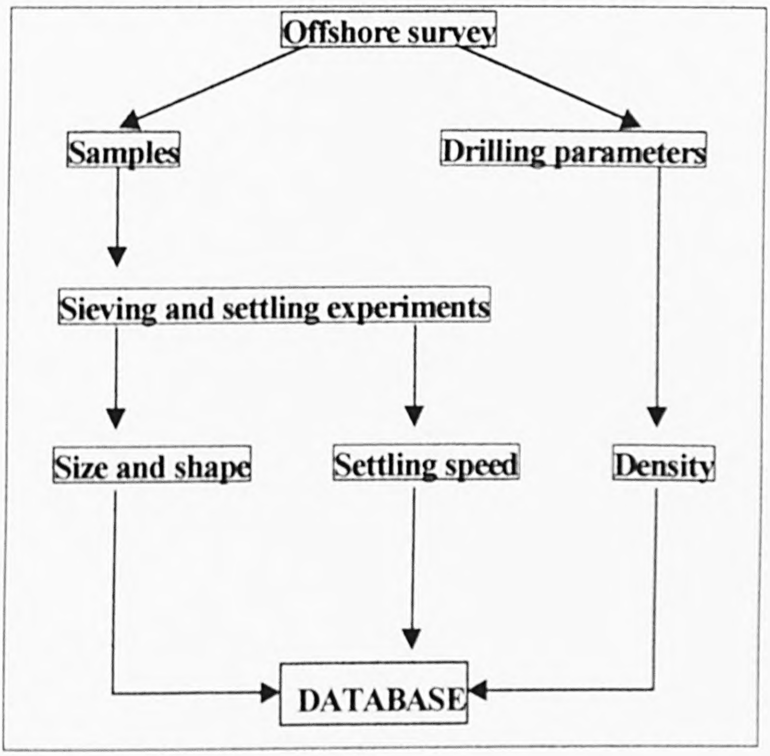


Figure 3.1: The general methodology for the collection of data.

In this chapter, the offshore survey as well as the laboratory and offshore experiments are described in detail. The disaggregation experiments are not mentioned in Figure 3.1 as they were only ranging experiments. They are described in section 3.6.2 and were mostly used for recommending further work (see section 7.3.1). The correlations between the drill-cuttings characteristics and the drilling parameters are dealt with in chapter.6. The need for the offshore survey was presented previously in this section.

The first step in running the offshore survey was to get the permission from the operators to run the offshore survey on their installations. Operators were approached and the drilling managers contacted. A presentation of the overall project was provided and the requirements for the survey described. In order to 'install' the survey on different offshore installations, three trips to four different rigs were made:

- Galaxy I: jack-up in the Central North Sea, operated by Elf Exploration plc;
- Sovex (Sovereign Explorer): semi-submersible in the Northern North Sea, operated (at the time) by Total Oil Marine plc; transfer to the North Alwyn: twin fixed platform in the Northern North Sea, operated by Total Oil Marine plc, and;
- Dunbar: semi-submersible (Sedco 706) attached to a fixed platform in the Northern North Sea, operated by Total Oil Marine plc; transfer to the North Alwyn.

As well as the 'implementation' of the survey, the aims of these trips were to acquire a practical knowledge in drilling techniques, see the solids control system in use, take some pictures for the thesis, and also to experience life on an offshore installation. Once the permission was obtained from the operators, adequate information was sent to the rig: one document to the 'company man' and another different document to the mudlogger. These two documents can be seen in Appendix.1. The first document presented the project to the 'company man' so he/she knew that the background to the survey and how the staff were involved. The document for the mudlogger contained guidances on running the survey and collecting samples. Once the well was finished or more regularly if required, the samples were sent from the rig to the laboratory along with the drilling data on floppy disks. During the entire survey, no major problem was encountered with the collection of data and samples.

3.1.2 Offshore survey

In order to conduct the offshore survey, a questionnaire for the mudloggers was provided, as a hard copy and on floppy disks. This questionnaire was sent at the same time as the previously presented documents with guidances. Two floppy disks per well were always provided: one to back-up the other. As can be seen on Table 3.1, the questionnaire was Excel-based and very straightforward to fill in. The mudlogger would usually have a copy of the document on the computer and would fill in the questionnaire when required. He/she would then take samples at the shakers at the relevant time. The samples were bagged and labelled, and stored in appropriate boxes. The boxes were sent regularly to the laboratory along with the drilling data on a floppy disk.

Well Name:				**Water depth (m):**		
Rig type:				**Latitude:**		
Section:				**Longitude:**		
Generalities:						
Start Date or date of the last sample						
Date of sampling						
TVD (m)						
Measured depth						
Drilled length (in the section)						
Total length of section (m)						
Type of bit						
Turbine: yes/no						
ROP (m/hr) of **lag depth**						
RPM of **lag depth**						
Mud weight (out) at **lag depth**						
Mud type						
Surface installations						
Scalper # 1: Screens						
Scalper # 2: Screens						
Shaker # 1: Screens						
Shaker # 2: Screens						
Shaker # 3: Screens						
Shaker # 4: Screens						
Shaker # 5: Screens						
Shaker # 6: Screens						
Centrifuge: ON/OFF						
Formation:						
Stratigraphy						
Lithology						
Density of cuttings						
Cuttings: (Size/Shape)*						
>3cm (%) + **A/F/R**						
3/1cm (%)+ **A/F/R**						
1/0.5cm (%)+ **A/F/R**						
0.5/0.1cm (%)+**A/F/R**						
<0.1cm (%)+ **A/F/R**						

Table 3.1: The questionnaire for the offshore survey.

One column per sample and usually one sheet per drilling section (17 1/2'', 12 1/4'' and 8 1/2'' for example) were used. The upper part of the questionnaire concerned the general drilling parameters at the time the sample was taken. A brief explanation of each term is given below:

- section: this is the drilling section (17 1/2'', 12 1/4'' and 8 1/2'' for example);
- date of sampling: this could be used as a back-up in case there is a problem with the data;
- TVD (m): True Vertical Depth (m): the depth at which the drilling bit is the geological formations knowing the depth is measured vertically (see Figure 3.2);
- Measured Depth (MD) (m): the measured length in metres that the drilling bit travelled since the start of the well (see Figure 3.2). If the well is only slightly deviated, then the TVD and the MD are very similar. If the well is highly deviated, the MD is drastically higher than the TVD. The two depths are usually referenced to the rotary table or the seabed.

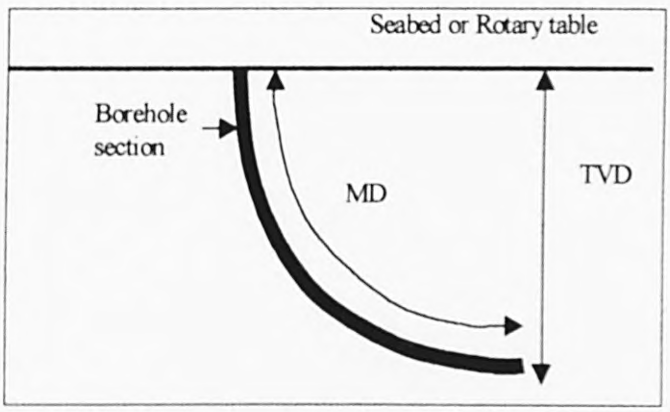


Figure 3.2: The difference between the TVD and the MD.

- Total length of section (m): this was to enable the calculation of the volume of cuttings per section if needed;
- Type of bit: name or type of the drilling bit used at the time of sampling. When the name only was provided, catalogues from bits companies were used to assess the type of bit used;
- Turbine (yes/no): this was to know if the turbine was on or not. The downhole hydraulic turbine motor is probably the most widely used directional tool. It is used in combination with other deviation tools. These are independent of the rotary system and are powered by the circulating fluids being used. The tool turns without

the rotation of the drill stem; rotation is produced by the flow of drilling fluid through the hydraulic turbine motor (Basic Drilling year unknown);

- ROP: Rate of Penetration, rate at which the drilling bit penetrates into the geological formations (m/hr);
- RPM: Revolution Per Minute, number of rotations of the drilling bit (rev/min). If the motor or turbine is on, then the bit RPM is equal to the drillstring RPM plus the turbine/motor RPM;
- Mud weight (out): weight of the drilling mud measured from a sample taken in the mud tank. All these parameters were requested at the 'lag depth'. In effect, there is a difference in time between the moment when the cuttings are being generated downhole and the moment when they come out on the shakers. This is the lag time. Asking the drilling parameters at the lag depth was asking the drilling parameters at the time (and depth) the cuttings were generated and not whenever they came out on the shakers;
- Size of the screens used on each shakers, and;
- Details about the cuttings: density, shape and ranges of sizes. First, the geological information such as the stratigraphy (i.e. the name of the geological layer, for example 'Balder') and the lithology (i.e. the nature of the rock, for example sandstone). The usual symbols for lithologies were: LST for limestone, SST for sandstone, CST for claystone.

Finally, a small sample (one cup) of cuttings from the shakers was analysed by the mudlogger for each change in the drilling parameters. An average percentage of each size indicated on the questionnaire was given by the mudlogger. At the time of the design of the questionnaire, it was hoped that these particle size distributions could be used for the database. Unfortunately, none of the rigs used exactly the same method to conduct this analysis (i.e. by sieving or/and by eye). Therefore, in the absence of consistency, this data was not used in the analysis of samples.

3.2. PREPARATION OF SAMPLES

3.2.1 Samples

First of all, the samples came in large boxes from various offshore rigs located in the North Sea (see Figure 3.3).

Figure 3.3: The samples (in boxes) from various offshore installations.

It is reminded that the sampling was done at the end of one of the shale shakers separating cuttings and drilling muds on board of the rig (see Figure 2.6 - photo of shale shakers with cuttings). The operator took the indicated amount of wet cuttings from the shakers and put the sample in a specific bag (labelled with the name of the well and the depth). Then all the bagged samples were put into large boxes. These boxes were loaded on the supply boat and brought back onshore. They were then either directly taken to the SMOE (School of Mechanical and Offshore Engineering) laboratory or at the company's offices (which would then forward them to the SMOE laboratories). There was an effort to try to keep this journey as short as possible and good conditions. However, it was kept in mind that due to the conditions of travel and handling of the samples, the drill-cuttings endured changes in their characteristics (size and shape in some cases). The extent of these changes were not qualitatively and quantitatively known.

Once the bagged samples were received from the different offshore installations, they needed to be analysed. In order to do so, an experimental methodology had been set up in the SMOE laboratories. Several experiments were conducted in this study. Details about the equipment and procedures for these experiments, transport and preparation procedures are described in this chapter. The two main experiments carried out were:

- meshing or sieving to obtain the size and the shape of the cuttings, and;
- settling of particles in a water tank to determine the settling velocities.

Efforts were made to obtain representative samples from the bagged samples. In effect:

- the sample taken from the shakers should be representative of the change in the drilling parameters;
- the sample taken from the original cuttings bag needed to be representative of that bag.

Therefore, the sub-sample needed to be 'randomly' taken from the bagged sample. A 'random' sample was one in which:

- every particle of the available total sample (in the present case the cuttings bag) had an equal chance of being included in the sample, and;
- each selection was made independently of all others.

A question arise: how different might the obtained size distribution be if it were computed from a different random sample of that same cuttings bag. This question was a part of the assessment for the 'precision of measurement', which represents a sort of reliability. To obtain a high level of reliability, precision and representativeness are important, but so is repeatability. Precautions were taken in order to fulfill these requirements (see 3.3.5.2). As a summary, the level of the representativeness depended on:

- the number of samples analysed;
- the quality of samples, and;
- the quality of the analysis.

3.2.2 Equipment

In this section, lists of the needed equipment for each task of the laboratory experiments is presented:

- Conservation of samples:
  - special bags (which can contain SBM cuttings without leaking) provided by the mudlogging companies (e.g. Geoservices), and;
  - large boxes containing the bagged samples.

- Transport of samples:
  - supply boat;
  - truck, and;
  - car.

- Preparation of samples:
  - detergents to wash instruments and recipients after use;
  - containers to wash cuttings if required ('wash cuttings' means 'get rid of the drilling mud');
  - plastic gloves (to avoid contact with drilling muds contained in the cuttings), and;

- Sieve apparatus:
  - sieves with range of mesh sizes (see Table 3.2);
  - small plastic bags (sandwich type of bags) for each range of size;
  - detergents to wash instruments after use, and brushes to get rid of unwanted material in the mesh;
  - little paint brush to move cuttings on the sieving medium if needed, and;
  - drilling mud for SBM cuttings only.;
  - drying paper;
  - hot-air blower, and;
  - analytical sieve shaker: AS 200 Basic from RETSCH.

Size (mm)	Type	British Standard
0.09	N.Greening-Hayes	BS 410/1969
0.15	Endecotts	BS 410/1986
0.5	N.Greening-Hayes	BS 410/1969
0.85	Endecotts	BS 410/1986
1.0	Endecotts	BS 410/1986
2.0	Endecotts	BS 410/1986
3.35	Endecotts	BS 410/1986
4.0	Endecotts	BS 410/1986
9.5	Endecotts	BS 410/1986
16.0	Endecotts	BS 410/1986

Table 3.2: The different sieves used for the sieving experiments.

- Mass measurements:
  - precision digital scale: METTLER PE 3600 Delta Range.

- Settling experiments:
  - water tank (50/40/150 cm);
  - digital video camera PANASONIC;
  - TV set, and;
  - digital stop watch.

3.3 SIEVE ANALYSIS

3.3.1 Size measurement methods

In this section, different techniques to measure the size of particles are presented. Finally, the sieve analysis is described as the selected option for the present study. First of all, the size and shape of a particle are briefly discussed.

A particle can be considered to have the following properties: volume, weight, surface area, projected area (surface area of the direct shadow of the particle) and sedimentation rate. The diameter of the particle is the most widely described parameter for the description of the particle. However, depending on the shape of the particle, the diameter can be the value of very different measurement: the sieve aperture, the maximum length, the minimum length, the average between the maximum and the minimum...etc (Rawle

1994). The variation between these diameters increases as the particles diverge more from the spherical shape, and hence shape is an important factor in the correlation of sizing analysis made by various procedures. That is why, very often the concept of 'equivalent sphere' is used. An 'equivalent sphere' can be a sphere of the same diameter, volume, surface area etc. as the particle and always needs to be properly defined as such. This concept is discussed again in Chapter.4.

There are several techniques to measure the size of the particles. Each of them has advantages and drawbacks, but should be adapted to the type of particles measured and on the aim and scale of the experiments. The different methods can be summarised as follows: sieving, electrozone sensing (Coulter Counter), microscopy, image analysis and laser diffraction (Rawle 1994).

The measurement used for the purpose of this study is the sieve aperture. Laser diffraction apparatus like the Malvern was not an option as the range of defined sizes is limited and comprises very small diameters of particles (from hundreds of microns up to less than a micron). The accuracy given for small ranges of size was not necessary in the present study. The attention was more focused on the bigger particles. An image analyser using a microscope attached to a computer was not either suitable as each cuttings would have had to be analysed separately. This would not have been representative or feasible in terms of time. Therefore, for these reasons, test sieving was the selected method for the present project.

Sieving consists of passing a sample through different meshes and determining the percentage of particles with the same size. Sieving tests are used in many industries: they are made on a wide variety of materials and for different purposes. No single method of single analysis can be specified to cover the many applications (British Standard 1976). The procedures depend on the predominant size range of the particles in a sample and it is recognised that some materials are difficult to sieve and require specially developed techniques. The principles to be followed in the sieving procedure will be similar in each case but the actual detail may vary considerably according to the purpose for which the results are required (British Standard 1976). A single test sieve separates a particulate material into two fractions, of which one is retained by the sieving medium and the other passes through its apertures. Test sieves are standardised in national standards such as BS 410 (in the present case, BS 410/1969 and BS 410/1986).

According to Allen (1981), the sieve diameter, for square-mesh sieves, is the length of the side of the minimum square aperture through which the particle will pass. In a sieving operation, such a particle will not necessarily pass through the appropriate mesh, particularly if it will only pass through when presented in a particular orientation as with elongated particles. For all such particles to pass through, the sieving time should approach infinity. There is also a range of aperture sizes in any sieve mesh and certain particles may only pass through the largest apertures. Moreover, the procedure is complicated when applied to particles of non-spherical shape. A specific particle with a size near that of the nominal aperture size of the test sieve may pass the apertures only when presented in a favourable position, and will not pass when presented in other positions. There is an inevitable variation in the size of the sieve apertures, but the proportion of oversize or undersize apertures is limited by the specifications for test sieves. Prolonged sieving and/or bad maintenance of the sieves also affect the variation in sieves apertures.

Another problem comes from the fact that, in many cases, the presence of fine particles can cause blinding of the sieve apertures and reduce the effective area of the sieving medium: blinding is likely to be most serious with test sieves of very small aperture size. The process of sieving may be divided into two stages: first, the elimination of particles considerably smaller than the sieve apertures, which should occur rapidly. Then, the separation of the so-called 'near-size' particles has to be achieved, but this is a gradual process that rarely reaches final completion.

3.3.2 Detailed procedures

This section presents the procedures undertaken for the sieve analysis. It describes each step and justification for selected methods.

First, it has to be noted that no sieve under 90 microns was selected. In effect, whenever smaller sieves were tried, the particles would rapidly cover the area of the sieve and block the whole system (blinding process discussed earlier in the section). It was understood that one way to overcome this problem was to either increase the number of sieves or decrease the weight of the total sample. An increase in the number of sieves would have meant a lot more total time and effort, with little advance in the necessary knowledge for this work. A decrease in the weight of the total sample would have endangered the representativeness. The reasons for choosing 150g were:

- tests, with 300g were failed each time because of too much material to handle on the sieves;
- an amount of 150g was the maximum that the stack of sieves could handle and was still thought to be representative, and;
- no problems were encountered with the sieves using a total weight of 150g.

Two types of methodologies were agreed and applied to the two different types of cuttings (WBM and SBM). For WBM samples, the method was based on wet-sieving and on dry-sieving for SBM samples. For both of them, all the sieves were firstly checked for size and state, then weigh dry and empty, and finally piled together in the sink from the smallest to the biggest diameter.

For the WBM cuttings, the method (based on wet-sieving) consisted in:

- taking 150g of cuttings from the sample bag;
- pouring some tap water in the recipient containing the 150g sample;
- shaking gently by hand to separate the agglomerated particles and also to separate the mud from the rock-cuttings;
- pouring the mixture on the sieve stack and rinse the recipient on the sieve not to loose any of the particles;
- rinsing each sieve one by one (starting with the biggest) to separate the different particles and to get rid of the mud;
- once an acceptable state of the subsamples was reached, the pile of sieves was put on the analytical sieve shaker (time: 5min, amplitude: 50). This step is shown in Figure 3.4.

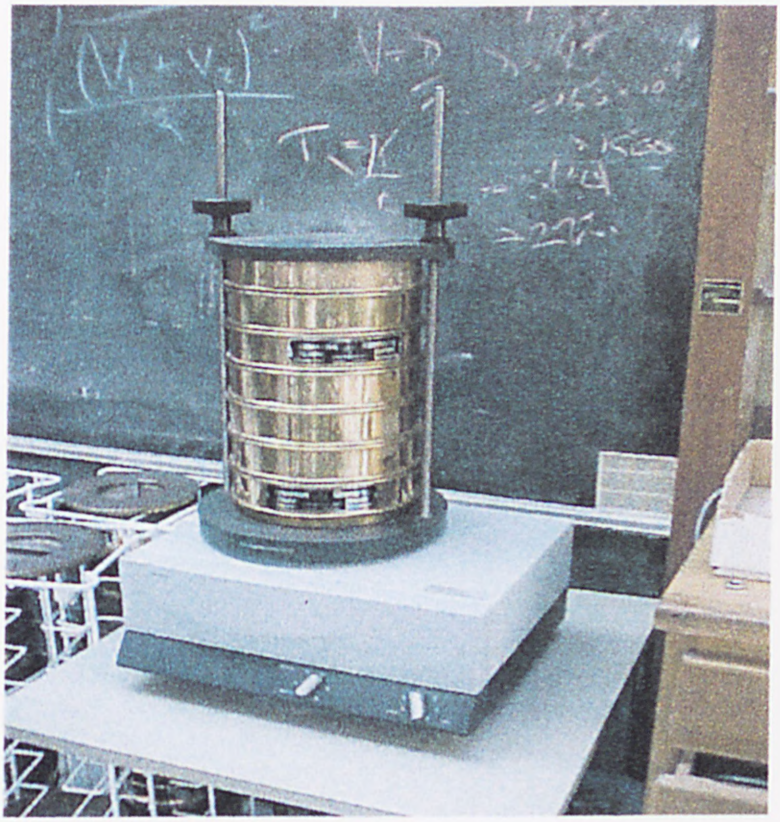


Figure 3.4: The stack of sieves on the analytical shaker.

- if needed, the subsamples were re-rinsed (sometimes, the 'shaking' got the subsamples muddy again) with tap water;
- each sieve containing the cuttings is then dried using the drying paper for the outside and the hot-air blower for the inside. For this operation, the sieves are still on the top of each other in case some particles, once dried would fall onto the next sieve. For the smallest sizes, a very fine sieve was placed on the top of the sieve being dried so particles, once dried, would not fly away;
- each sieve was weighed again with the dried subsample on it. At this stage, the shape analysis was conducted by visual assessment and monitored as F, A and R (see section 3.3.3, and;
- the subsamples were placed in small sealing plastic bags with a label indicating the number of the sample and the size of the sieve the particles went through.

For the SBM cuttings, the method (based on dry-sieving) was slightly different:

- a sample of 150g from the bag was taken;
- the sample was rinsed with the appropriate SBM to separate the particles;
- the mixture was poured on the first sieve. In this case, a container was placed at the bottom of the pile in order to get the SBM back and not let it go into the sink;

- because of the stickiness of the particles, the subsamples were then dried directly with the hot-air blower;
- once the subsamples were dried, the pile of sieves was put on the analytical sieve shaker or/and was shaked by hand until all the particles (as much as possible) end up in the adequate sieve;
- each sieve was weighed again with the dried subsample on it, and the shape was visually assessed in the same way as for WBM samples;
- the subsamples were placed in small sealing plastic bags with a label indicating the number of the sample and the size of the sieve the particles went through.

A total of 35 samples were analysed using the stated procedures. The presentation of data is dealt with in section 3.3.5.

3.3.3 Assessing the shape

The shape is an important characteristic of the particle and was visually assessed at the same time as the sieving tests. Qualitative terms may be used to give some indication of the nature of particle shape and some of these, extracted from the British Standard 2955 (given in Allen 1981):

- Angular (A): sharp-edged or having roughly polyhedral shape;
- Flaky (F): plate-like, and;
- Spherical (R- for round): global shape.

Sphericity is not an absolute number and there were a lot of debates on what it means and how it should be quantified. Wadell (1932) and Wentworth (1932) had a published fight on the subject in 1932. Their respective point of view was very interesting to read, and their work was probably the genuine background of the actual definitions of sphericity and roundness. However, the problem is still the same: is there a universal equation for sphericity? Can the available definitions be applied to every type of particles? And most difficult of all: how can it be accurately and conveniently measured through experiments? A very common and accepted way is to associate the particle with an equivalent sphere (i.e. sphere with a similar physical characteristic: volume or surface area for example). But it is indeed sometimes difficult to measure the volume or surface area of the particle, especially when the particles are fragile and numerous (which was the case for the present study).

First of all, the sphericity is widely defined by the following equation:

$$\psi_p = \frac{A_{eq}}{A_p}$$

(Wadell 1932)

For visual assessment, some information (Wadell 1932, Geoservices 1994 and Rawle 1994) was found in order to determine the overall shape of the particles. Figures 3.5 3.6 and 3.7 show the different 'charts' found in those documents.

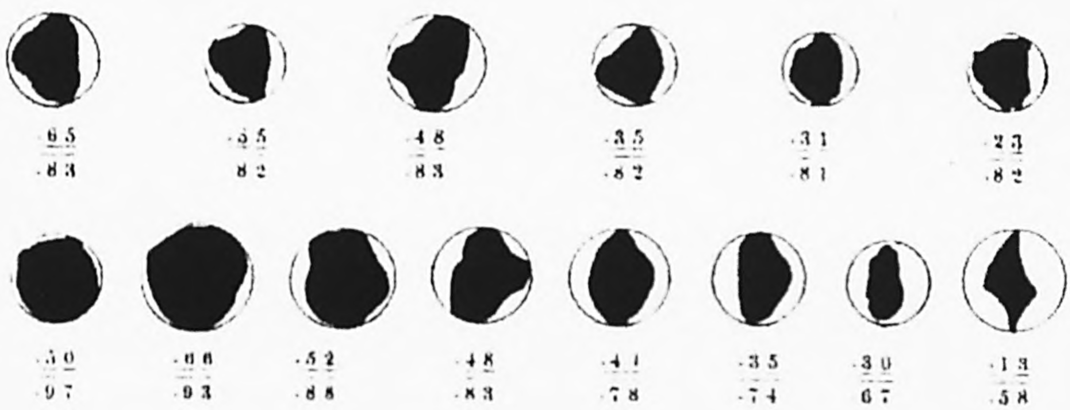


Figure 3.5 Chart for particles shape from Wadell (1932).

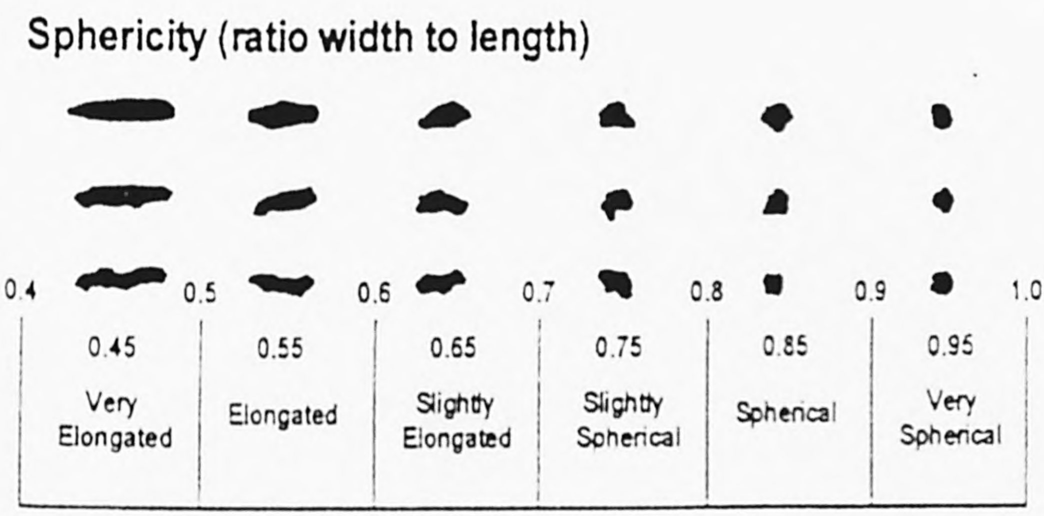


Figure 3.6 Chart for particles shape from Geoservices (1994).

In this figure, the sphericity is defined differently than in Wadell's document: it is a ratio between the width and the length of the particle. However, the increase (from left to right) in sphericity is shown which helped in the visual assessment.

Figure 3.7 Chart for particles shape from Rawle (1994).

It was understood that a visual assessment of the shape is very subjective. However, 'standard references' were set up, and the experimentor tried to respect them as much as possible. These standard references can be seen in the following series of photos (see Figure 3.8-3.11). The photos show typical examples of each shape: angular-round, angular, angular-flat and flat drill-cuttings.

Figure 3.8: Angular-round drill-cuttings.

Figure 3.9: Angular drill-cuttings.

Figure 3.10: Angular-flat drill-cuttings.

Figure 3.11: Flat drill-cuttings.

These photos were taken using large particles so the shape would be obvious. However, for small particles (under 0.5 mm), the shape was always assumed to be very round (see Figure 3.12). The strongest zoom capacity of the camera was used to show the small particles.

Figure 3.12: Small drill-cuttings assumed to be very round.

Using these references for shape and the charts presented previously, the sphericity factor could be determined. The following table summarises the values for the sphericities.

Shape	Sphericity
sphere	1
round	0.9
angular-round	0.8
angular-flat	0.6
flat	0.5
flat-round	0.4

Table 3.3: Sphericity values for the drill-cuttings.

When drilled with PDC bits, the flat-round particles could be assumed to be cylindrical. The flat particles were often very flat in terms of thickness but still angular on that surface (see Figure 3.11). That is why the sphericity for flat particles is higher than that of the flat-round ones. In effect, the flat-round particles were usually very elongated compared to the flat ones. Therefore, according to Figure 3.6, their shape factor (in terms of ratio width to length) is lower. For angular-flat particles, the angularity could be observed in three-dimensions. This is the reason why their sphericity is even higher.

3.3.4 Quality control on the sieve analysis

<u>3.3.4.1 Sources of errors</u>

In any experimental tests, sources of errors are numerous and can cause bad quality of the obtained data. In every case, these sources have to assessed, and then precautions have to taken to minimise errors. This section presents the list of sources of errors. There are many sources of errors and the difficulties to quantify them are high. Therefore, it was prefered to state them in detail as above and to keep aware of them in the analysis and conclusions, rather than to try to quantify them at all cost, using guesstimates for most factors. For the samples and sieve analysis, the sources of errors were as listed below:

- For the samples

The quality of the samples depended on:

- the attention the mudlogger paid when he/she collected and handled the samples offshore;
- the weather and sea conditions during the trip from the offshore installation back to the laboratory (by boat and then by truck);
- the quality of the handling in between the different locations (i.e. rig/boat/truck/warehouse/truck/laboratory), and;
- the carefullness of the experimentalist when taking a subsample from the sample and dealing with it.

- For the sieve analysis

Errors from sieving measurements came from various sources and are divided into three categories:
- the equipment;
- the experimentalist, and;
- the samples.

The equipment for the present study consisted in: sieves, a sieve shaker, a digital scale and an air blow dryer. The manufacturer gave the following accuracy for the digital scale: 0.01grams. As far as the sieves were concerned, the main errors were:

- from the measurements and homogeneity of the apertures;
- from the variations in the diameters of the wires;
- from the quality of the wires;
- from the fact that some apertures are actually rectangular rather than square (this will enhance the problem of orientation of the particle when passing through the sieve), and;
- from the state of the sieves (directly linked to the quality of the sieves, the maintenance and the frequency of use).

For the scale and the shaker, the accuracy of measurements or conditions of use was given by the manufacturer. From the experimentalist, the main errors were due to:

- the unlikelihood that the experimentalist would dry every sample in the exact same way for the exact same time even if standard procedures were set up;
- the unlikelihood that when shaking by hand was involved, this would be done in the exact same way for every sample, and;

- the fact that every sieve was probably not 'perfectly' dry in between two tests, therefore changing slightly their weight.

3.3.4.2 Precautions

In order to minimise the effects of the presented sources of errors, precautions were taken. They are listed below:

- the offshore survey was designed offshore with the help of drilling engineers, geologists and mudloggers so it would be adapted to their routine and the requirements of the present study;
- the journey from offshore to the lab was kept as short and careful as possible;
- once in the labs, the samples were used as soon as possible to avoid natural degradation;
- the equipment was always kept in good state and checked before use;
- the precision scale had been calibrated prior to the first test;
- during experiments, the experimentor tried to be as consistent and regular as possible, strictly following the designed procedures and always using the same equipment, and;
- a second sub-sample from the same bag was regularly taken for a second sieve analysis.

Six samples out of 35 were 're-sieved' for a simple repeatability test. The results of this comparison are presented below in terms of percentages of errors between the first and second analysis (see Table 3.4).

Error (%)
19.49
9.35
4.37
4.37
2.75
0.71
1.66
7.12

Table 3.4: A second sieve analysis for comparison.

The bottom number (in bold) is the average error over the six samples. As observed in the table, the maximum error was 19.49% and the minimum was 0.71%. The average error (7.12%) was judged to be acceptable.

3.3.5 Presentation of sieve data

The procedures for experiments have been detailed and the sources of errors and consecutive precautions have been listed. The data is now presented with the cuttings size distributions first and then the complete set of data.

3.3.5.1 Cuttings size distributions

In order to collect the data from the sieve analysis, Excel-based datasheets were created. Whenever measures are arranged in order of magnitude and a density is recorded for each magnitude, the result is a 'density distribution' (Phillips 1992). Here, density distributions showing the percentage of cuttings of each size for each sample has been obtained. Normally, the information obtained from the test sieving is plotted as a cumulative distribution (see 'Cum-curves' in Figure 3.13): the abscissa is the particle size and the ordinate, the percentage smaller or bigger than the size. When the cumulative weight percentages were calculated, two methods were available:

- oversize: 100% corresponds to the smallest, and;
- undersize: 100% corresponds to the biggest.

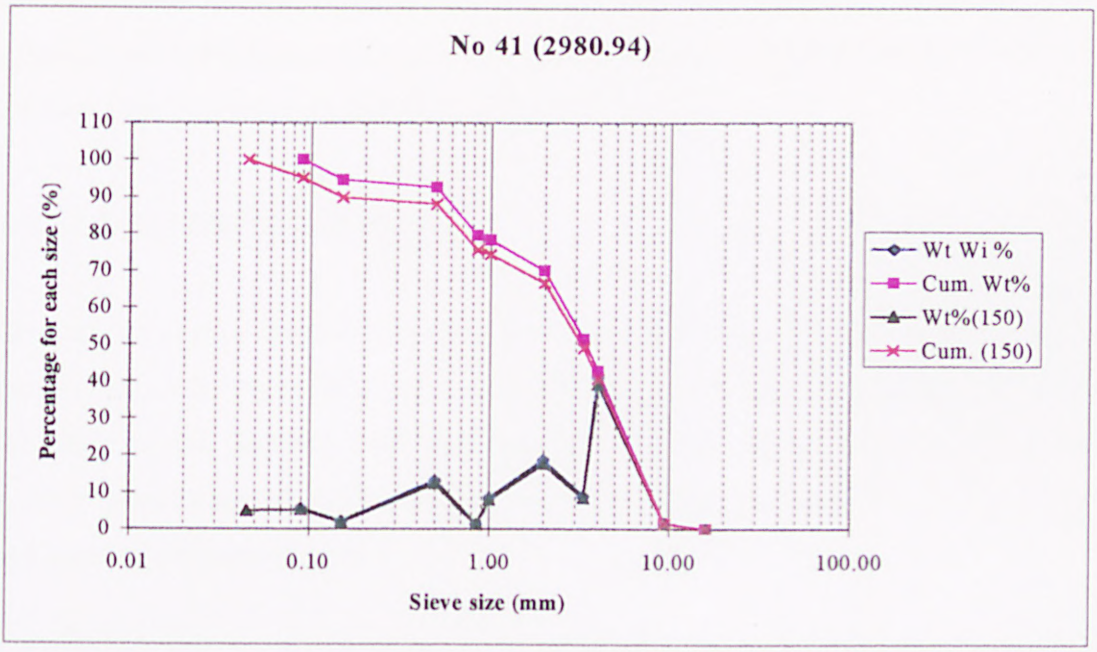
Because the particles having a size smaller than 90 microns could not be kept at the end of the experiments, it was difficult to know the percentage of particles of that size. Two ways to deal with this problem were to:

- assume that this percentage corresponds to the difference between 150 g and the total cumulative weight (the '150 method'), or;
- neglect the particles of that size and only deal with particles with a sieve diameter bigger or equal to 90 microns (the 'cumulative weight method').

If there was not a large percentage of these particles, then the two methods were very similar. However, when the percentage of very small particles was very large, then the two methods differed significantly. For WBM samples drilled in soft clay formations for example, there is a significant difference between the two. This is because of the high percentage of very small particles (smaller than the smaller sieve). Each sample data was presented using the two methods so the difference between the two methods could be assessed. In what was called the '150 method', the sieves were weighed as per normal. Then, if the total weight was found to be less than 150 grams, the difference was assumed to be the weight of the particles smaller than 90 microns. In the 'cumulative weight method', there was no assumption for the particles smaller than 90 microns. All the percentages were calculated using this total for reference (as opposed to 150 grams in the '150 method'). This difference gave their names to the methods: the first one uses the cumulative weight (the sum of all the sample weights left on each sieves) as a reference, and the 150 method uses 150 g as a reference. An example of raw data from sieving experiments is shown below:

Sieve size (mm)	Wt Wi %	Cum. Wt%	Wt%(150)	Cum. (150)
16.00	0	0	0	0
9.50	0	0	0	0
4.00	2.77	2.77	1.75	1.75
3.35	2.28	5.05	1.43	3.18
2.00	2.69	7.74	1.69	4.87
1.00	15.69	23.42	9.88	14.75
0.85	5.98	29.40	3.77	18.52
0.50	30.45	59.85	19.18	37.7
0.15	25.01	84.86	15.75	53.45
0.09	15.14	100	9.53	62.99
0.045			37.01	100

Table 3.5: An example of raw data from sieving experiments.



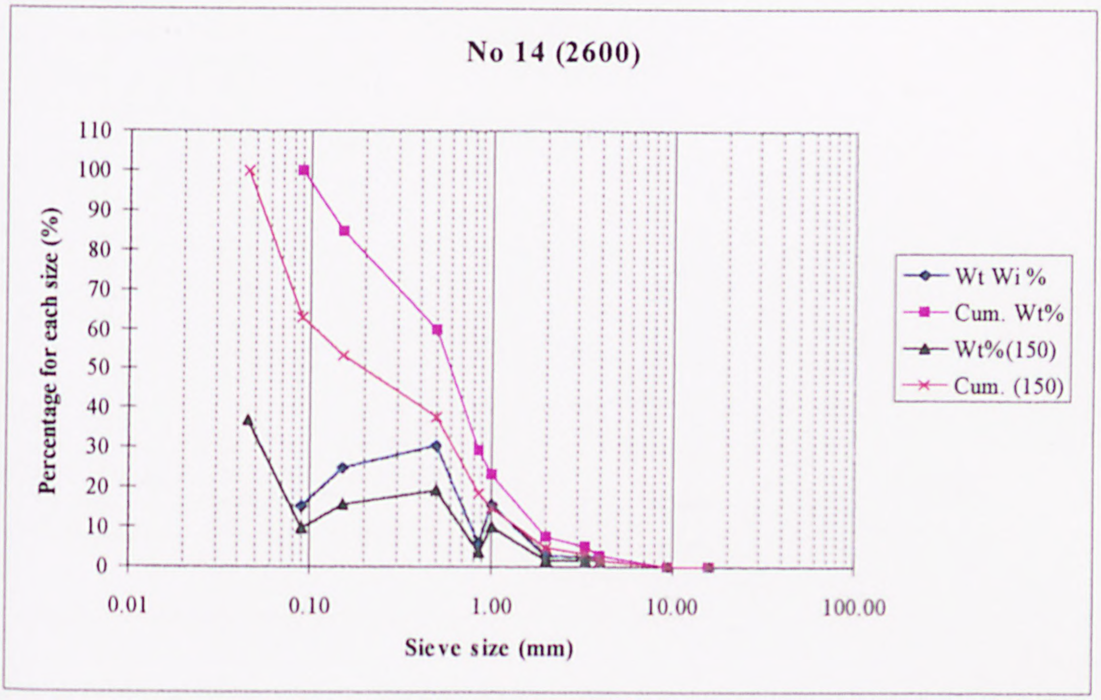


Figure 3.13: Two examples of graphs from sieving data.

For sample No 14, it can be noticed that there was a great difference between the Wt% curve and the Wt% (150) curve. This difference is much smaller for the curves corresponding to sample No 41. Therefore, depending on the sample, and especially the conditions under which the sample was drilled, the two methods could give different results. However, for the purpose of this work, one of the methods had to be chosen and all the samples analysed using one method only. In the present case, the 150 method was chosen because the percentage for the last size range was thought of great value. All the cuttings size distributions (using the '150 method') are shown in Appendix.2, along with the data from Norway (see section 3.4.1).

3.3.5.2 A complete set of data

One of the main objectives of the present study was to correlate the cuttings size distributions with the drilling parameters. From the laboratory experiments, the size and the shape of the particles were obtained. The drilling parameters associated to every particle were known from the offshore survey. Therefore, at that stage, all the data was put together for each sample.

Section	12.25
TVD (m)	2528.5
Drilled length (in the section)	247
Total length of section (m)	1426
Type of bit	DBSQ19L
Turbine yes/no	no
ROP (m/hr) of lag depth	37.56
RPM of lag depth	165
Mud weight (out) at lag depth	1.38
Mud type	silicate
Scalper # 1: Screens	
Scalper # 2: Screens	
Shaker # 1: Screens	10/84
Shaker # 2: Screens	10/180
Shaker # 3: Screens	10/145
Shaker # 4: Screens	10/145
Shaker # 5: Screens	
Shaker # 6: Screens	
Centrifuge: ON/OFF	
Stratigraphy	U.Cret
Lithology	Clyst
Section	12.25
TVD (m)	2585

Sieve size	16	9.5	4	3.35	2	1	0.85	0.5	0.15	0.09
Shape			F	F	F	F	F	R	R	R

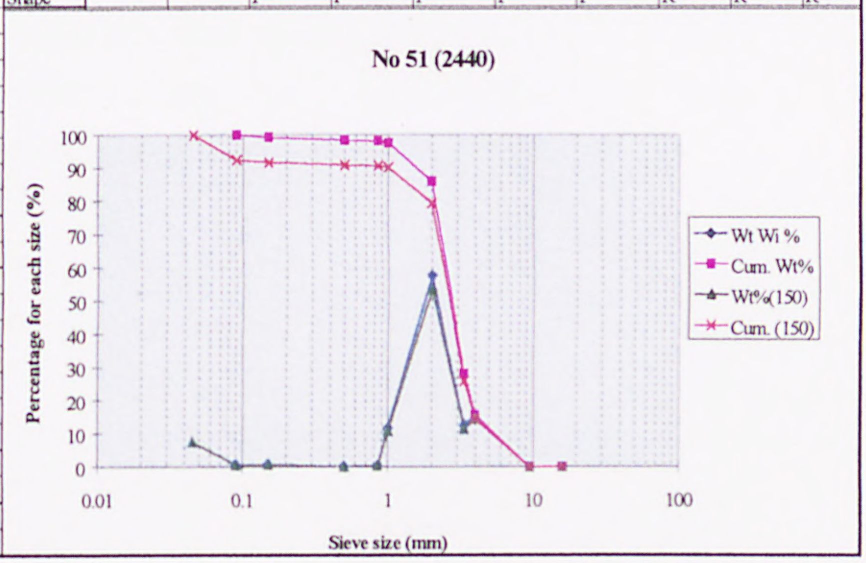


Figure 3.14: An example of a complete set of data.

In this Figure, the drilling parameters are shown on the left hand side, the shape is given at the top and the central graph represents the particle size distribution (with the four curves included). This is a unique set of data which was obtained for every 35 samples analysed. As stated in Chapter.1, one objective of the present work was to study the correlations between the drilling conditions and the cuttings size distributions. Using these complete sets of data, this could be achieved. Chapter.6 presents the development of the correlations using a statistical package. The data created by the author was not the unique set of data used for the correlations. A Norwegian company had also generated similar data using a similar method. This data was kindly given to the author who formatted it to comply with the requirements of the present work before analysing it with her own data. This process is presented in the next section.

3.4 SUPPLEMENTARY DATA

3.4.1 The Norwegian data

Cuttings size distributions was given by a Norwegian oil company. They came from one specific well in the Norwegian sector of the North Sea. This well had three sections with cuttings return (like most of the wells in the North Sea): 17 1/2", 12 1/4" and 8 1/2". Twenty two samples were taken at regular intervals along these sections. The data was given after sieve and Malvern (i.e. a light scattering based particle sizer) analysis in the form of tables and graphs (cumulative weights and size densities). This data differed from those obtained in the UK sectors in terms of format:

- the Norwegian analysis covered a wider range of sizes, a Malvern analysis having been performed after sieving. This gave a much more accurate analysis of the small particles;
- the Norwegian samples were sieved through a different series of sieves than that of the author's experiments.

Therefore, in order to use this data for the present study, it was decided to use linear interpolation to format the Norwegian data. Linear interpolation is a simple and common concept and is given by (Swan 1995):

$$y = y_1 + \frac{x - x_1}{x_2 - x_1}(y_2 - y_1)$$

if the point A (x,y) is the one to be interpolated in between the two points 1 (x_1, y_1) and 2 (x_2, y_2). The method assumes a straight line between points 1 and 2 (Schelkunoff). A specific datasheet was created to automatically calculate the interpolated values between two known values of cumulative weights. The weight of the analysed samples was 1 kg. The samples were initially sieved to remove the coarse cuttings with the reminder being analysed in the Malvern. Therefore, the cumulative weight was always very close to the original 1 kg. Only certain points of the cumulative curves could be used for the interpolation (the other ones were out of range). They are listed below:

- 8, 4.6, 1.7, 0.6, 0.544, 0.404, 0.301, 0.203, 0.102 and 0.0834 (all in mm).

So the common points between the UK and Norway data were:

- 4, 3.35, 2, 1, 0.85, 0.5, 0.15, 0.09 and 0.045 (all in mm).

After the interpolation analysis, the Norway and UK data was in the same format and could be used for the database. The total number of available samples was therefore 57 (35 from UK and 22 from Norway). The cuttings size distributions from Norway can also be found in Appendix.2. These curves were the base for the correlation analysis. Nine points from each curve were correlated to the selected drilling parameters. The correlation analysis is presented in Chapter.6.

3.4.2 The disaggregation experiments

Disaggregation experiments were conducted by the author using fresh cuttings on an offshore installation. Disaggregation processes are complicated and these were only ranging experiments. In brief, disaggregation is the process by which a particle breaks down into fine particles. Because these experiments were only ranging experiments, the background, procedures and results are presented in Appendix.3. The reasons for studying briefly the disaggregation of cuttings were to:

- observe a phenomenon which had been noticed several times during the sieving experiments;
- conduct ranging experiments in order to have a better knowledge in the field;
- verify if the obtained size distributions were always valid, and;
- use the results for suggestions for further work (see section 7.3.1).

The needs for studying the disaggregation of drill-cuttings in either drilling fluids or seawater are numerous and of great importance. For example, some clay formations just instantly disaggregate in the drilling fluid to very fine particles. The fact that the drill-cuttings disaggregate in the drilling mud changes the rheology of that mud and also the relative speed of the particles within that mud. And, therefore, the hole cleaning process is completely different. For example, a noticeable increase in the viscosity of the mud can be observed (Hervot 1999). Another need is to check if the cuttings size would change drastically after disaggregation. The disaggregation of cuttings in seawater for example would change the size distributions found from this study. This would induce different dispersion properties of the discharge in seawater.

As a summary, it can be said that the results from the experiments could not allow any constructive scientific conclusions. The processes of disaggregation involve knowledge in the chemical composition of the muds, the properties of the rock and the reactions occurring. The experiments simply showed that in some circumstances (especially when the clay is compact), disaggregation processes do not occur in short time. This was demonstrated under static and dynamic conditions. However, it was observed during settling speed measurements that WBM cuttings coming from soft clay formations had a tendancy to disaggregate rapidly. On another hand, SBM cuttings were never observed to disaggregate even after shaking and a long stay in water. This was believed to be caused by the coating of SBM around the cutting, making it 'waterproof'.

3.4.3 Density of drill-cuttings

The density of drill-cuttings was not assessed in the SMOE laboratories. Data was given by offshore mudloggers. The average density over a certain period of time was calculated. A value of 2390 kg.m^{-3} was found over 64 values for dry cuttings. Geologists usually consider the range bewteen 2.0 and 2.7 for the specific gravity of dry cuttings. The calculated value corresponds well with the average of this range: 2.35 SG. Therefore, when the density of cuttings is involved in the present document, the following is applied: $\rho_p = 2390$ kg.m^{-3}

3.5 SETTLING SPEED EXPERIMENTS

3.5.1 Detailed procedures

In order to measure cuttings settling speeds, a special water tank (see Figure 3.15) was built in SMOE laboratories. Equipment for these experiments was detailed in section 3.2.2. For the purpose of the present study, the settling speed is defined as the terminal velocity of the particle falling in static water. No resuspension or redeposition of the particle was considered. The water tank was made of thick perspex and comprised a main rectangular tank, re-inforced by a steel frame, a rectangular nozzle and a removable bottom. The bottom of the tank was removable in order to enable the removal of deposited cuttings. Two lines, one metre apart can be observed on the front face of the tank. The time of settlement was measured between these two lines. The dimensions of the tank were: 50/40/150 cm. The tank needed to be high enough to allow the particle to reach its terminal velocity before the first line.

Figure 3.15: A picture of the water tank used for the settling experiments.

The following procedures were applied to measure the settling speed of cuttings:

- the tank was filled with tap water to a level just under the overflow;
- a single particle was dropped from a centre point in the perfectly static water, and;
- the time of settlement was measured.

In order to measure the settlement of both big and small particles, two methods were applied:

- for big particles, a digital video camera was used to record the settling and deduce the time, and;
- for small particles, time was measured using a stop watch.

Particles smaller than 2.00mm could not be seen with accuracy on the video. Moreover, they settled very slowly. Therefore, the time could easily be measured using a digital stop watch. For particles bigger or equal to 3.35mm, the digital video camera was used. The settling was recorded and visualised on the TV set. Using the frame-by-frame function (25 frames per second), the settling time could be measured with high accuracy. Figure 3.16 shows an example of a record using the video camera. On this figure, a large particle can be seen, settling down in the water tank. In any case, the process was repeated for six particles of the same sample. The average speed was then taken to be representative of that sample.

Figure 3.16: An example of visualisation for the settling experiments.

3.5.2 Validation exercise

Before all the tests could be undertaken, the method using the digital video camera needed to be validated. In other words, the methodology needed to be tested, and the results compared to known data. In the present study, the best way to validate the method was to measure the settling time of spheres and compare the results with calculations. Two types of particles were used for this purpose:

- spherical particles made of Teflon with a diameter of: 9.525mm
- spherical particles made of Teflon with a diameter of: 3.175mm.

As stated earlier, two lines had been drawn one meter apart on a face of the tank. The particle was observed while travelling from one line to another. The time measured for the duration of this journey was then used to calculate the speed of the particle. The particle was dropped in the water without any initial velocity and was assumed to have reached its terminal velocity before the 'start line'. All the particles used for the validation tests were assumed to be perfectly spherical and with an homogeneous density. A precision scale (the same as for the sieving experiments) was used to weight the particles. For the smaller ones, five of them were weighted and the mass was divided by 5. In effect, the precision of the scale and the weight of the small particles were such that to weigh only one particle would have given a meaningless value.

For the big particle: $m_1 = 1.0$ gr $= 10^{-3}$ kg

For the small particle: $m_2 = 0.038$ gr $= 0.038.10^{-3}$ kg

Then, the volumes were calculated:

$$V_p = \frac{4}{3}\pi.r_p^3$$

So, $V_{p1} = 4.52.10^{-7}$ m^3 and $V_{p2} = 1.68.10^{-8}$ m^3

First of all, the density of the two types of particles was calculated:

$$\rho_{p1} = \frac{m_{p1}}{V_{p1}} = \frac{10^{-3}}{4.52.10^{-7}} = 2212.39\text{kg.m}^{-3}$$

$$\rho_{p2} = \frac{m_{p2}}{V_{p2}} = \frac{0.038.10^{-3}}{1.68.10^{-8}} = 2261.90\text{kg.m}^{-3}$$

Then, the settling speeds were evaluated. The settlements were first recorded using the camera. The times at the start and end lines were monitored using the fram-by-frame function (25 frames per second). The difference between the two was then calculated, giving consecutively the settling speed.

Test 1/ Big particle: $t_{11}= 1.8s$

So $v_{11}= 1/1.8 = 0.55\ m.s^{-1}$

Test 2/ Big particle: $t_{12}= 1.76s$

So $v_{12}= 1/1.76 = 0.57\ m.s^{-1}$

Test 1/ Small particle: $t_{21}= 3.56s$

So $v_{21}= 1/3.56 = 0.28\ m.s^{-1}$

Test 2/ Small particle: $t_{22}= 3.36s$

So $v_{22}= 1/3.36 = 0.30\ m.s^{-1}$

This was done for 6 particles of each type and the average values for the measured speeds were therefore:

$$v_{m1}= 0.548\ m.s^{-1} \quad \text{and} \quad v_{m2}= 0.303\ m.s^{-1}$$

To be able to compare the measured speed with the theoretical speed, the Reynolds number of the particles needed to be evaluated in order to choose the right theoretical equations.

$$R_{ep} = \frac{\rho_f d_p v_p}{\mu_f} \text{ (dimensionless)}$$

At 15 degrees Celsius, which was about the temperature of the water in the tank, the properties of the water were as follows (Hughes *et al* 1967):

$\rho_f = 999.13\ kg.m^{-3}$

$\mu_f = 1.145.10^{-3}\ kg.m^{-3}$

So $\quad R_{ep1} = 4554.72$

Here, the regime of the particle was turbulent.

And $\quad R_{ep2} = 839.47$

Here, the regime of the particle was turbulent as well.

For all these cases, it was assumed that the drag coefficient had a constant value of:

$C_D = 0.44$ (Kay 1963)

Then, the theoretical speeds were calculated according to the well-known formula (Kay, 1963):

$$v_{th} = \left[\frac{4}{3}\frac{d_p(\rho_p - \rho_f)g}{C_D\rho_f}\right]^{1/2}$$

So $\quad v_{th1} = 0.586\ m.s^{-1}$ and $v_{th2} = 0.345\ m.s^{-1}$

The average value of the measured speeds was:

$v_{m1} = 0.548\ m.s^{-1}$ and $v_{m2} = 0.303\ m.s^{-1}$

Therefore the difference between the experiments and the theory was:

- for the big particle: $0.038 m.s^{-1}$
- for the small particle: $0.042 m.s^{-1}$

These numbers were judged to be totally acceptable. Therefore, the validation exercise was successful and the settling experiments could be conducted.

3.4.3 Quality control on the settling speed measurements

3.4.3.1 Sources of errors

As for the sieve data, the quality of the settling data depended on the equipment, experimentalist and samples. The equipment consisted of either the digital video or the digital stop watch. Their absolute precision was given with the manufacturer guides:

- 25 frames per second for the digital video camera, and:
- 0.01second for the digital stop watch.

The word 'lag' can represent the time elapsed between the passing of the particle and the record of the stop watch. The lag of seeing and recording on the stop watch by the same observer can be called a 'single lag' as it is the result of a single brain (Richards 1908). This lag has a significant influence on the quality of the data. When using the digital stop watch, the error was due to its accuracy (0.01 sec) and the lag.

In the case of the video camera, the error on the measured distance depended on the distance between the video camera and the tank, the distance enclosed in the image, the angle of the video lens and also the effect of any zoom (if present). The error on the time is a function of which frames were decided to be the start and end frames. This error was assumed to be of one frame. There were 25 frames per second, so the error on the time was: 0.04s.

Another source of error came from the particles. The accuracy with which the size was defined induced a consistency in the selected particles from the same sample. The way the particle was dropped could also affect the regularity of the settling.

3.4.4.2 Precautions

A large number of precautions were taken in order to minimise the effects of errors on the settling speed measurements. They are listed below:

- after filling the tank with water, a certain time elapsed before any measurement in order to stabilise the water;
- the particles were dropped one by one from a selected initial point. This was to avoid influence from particle concentration and wall effect;

- six particles of each selected sample were used and the average settling speed was taken to be representative of that sample. A total of 187 measurements were taken using either the stop watch or the digital video camera. These 187 measurements gave average settling speeds for 32 different particles (2 for the validation exercise and 30 for further analysis);
- a small wet painting brush was used to drop the particle in the tank. The particle would then not contain air bubble when settling down. Moreover, the fragile particle would not be damaged prior to immersion;
- when using the stop watch, a second operator was present. One would drop the particle and the other would measure the time. The measuring operator would be waiting for the particle to cross the start line to start the watch. He/she would then follow the particle until the end line and stop the watch. This method minimises parallax problems and maximises accuracy on the measurements.

3.4.5 Presentation of the settling data

Table 3.6 presents the results from the settling experiments. As it can be noticed, the sizes of particles are different than that of the sieving data. In effect, when the settling experiments were conducted, particles from a bagged sample were used. The particles were chosen randomly from the sample, therefore they could have a size varying from the biggest to the smallest size of the range. It was then normal to say that, if the particles were chosen randomly in the sample, their average size was the average of that sample. For example, for particles chosen from a size range of 0.004/0.00335m, the calculated average size was: 0.003675m.

Size	**Vexp**	**Size**	**Vexp**
(m)	(m/s)	(m)	(m/s)
0.00675	0.131	0.000925	0.085
0.00675	0.165	0.000925	0.071
0.003675	0.075	0.000925	0.088
0.003675	0.121	0.000925	0.078
0.003675	0.149	0.000675	0.052
0.002675	0.096	0.000675	0.035
0.002675	0.134	0.000675	0.071
0.002675	0.118	0.000675	0.053
0.002675	0.186	0.000675	0.045
0.002675	0.157	0.000325	0.039
0.0015	0.063	0.000325	0.04
0.0015	0.1	0.000325	0.031
0.0015	0.135	0.000325	0.033
0.0015	0.123	0.00012	0.009
0.000925	0.047	0.00012	0.011

Table 3.6: The experimental settling speeds values.

The data was also plotted as a function of the particle size. These results can be visualised in Figure 3.17.

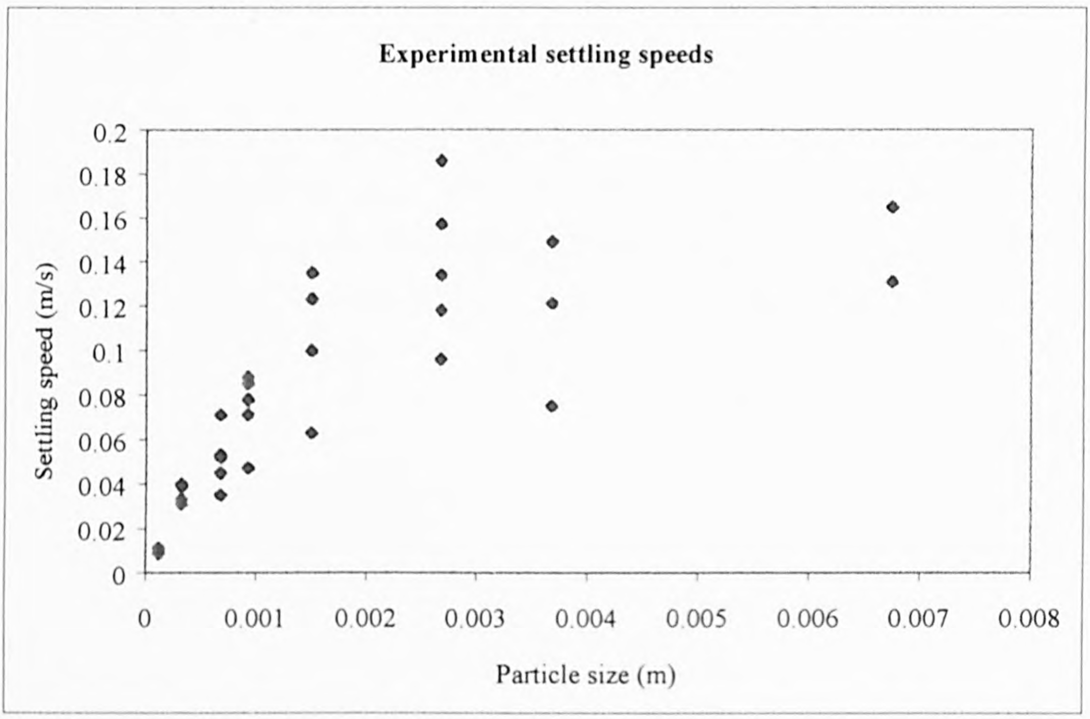


Figure 3.17: Experimental settling speeds values.

An interesting observation from this table is that particles with the same size could have different speeds. Some of them are vary to a great extent. In effect, each group of 6 particles used for each point was from a different sample and therefore had a different shape. It could also come from the fact that the density was slightly different from one sample to another. All the results from the settling experiments are presented in Appendix.4. The analysis of this data is dealt with in Chapter.4 and Chapter.5.

3.6 SUMMARY

Chapter.3 presented the experimental work of this study. It described the background and procedures for the sieve analysis and the settling speed measurements. The sources of errors and precautions to minimise these errors were also discussed. They show the difficulty in keeping the data consistent, accurate and representative. Moreover, luckily, data from a similar sieve analysis conducted in Norway was given for the benefit of the present study. Cuttings size distributions were then plotted for both UK and Norway sectors samples. Settling speed curves were also drawn as a function of the cuttings size. Disaggregation ranging experiments were briefly conducted and are presented in details in Appendix.4. They also lead to some recommendations for further work (see section 7.4.1).

From the sieving and settling experiments, the characteristics of cuttings (i.e. shape and size) and the aquatic settling properties were obtained. Along with the drilling parameters, they form a unique set of data. The settling speed data is further analysed in Chapter.4 and Chapter.5. The correlations between the cuttings size and drilling parameters are analysed in Chapter.6.

Chapter.4

ANALYSIS OF CUTTINGS SETTLING SPEED

4.1 INTRODUCTION

In Chapter.3, settling speed experiments were described. In Chapter.4, the cuttings settling speed is analysed. The main reason for studying the settlement of drill-cuttings is to introduce more adapted equation into cuttings dispersion models for example. Moreover, the study of the drag coefficient of drill-cuttings is also vital for the applications presented in Chapter.1.

First, general information about the settlement of a particle and the forces involved are presented. Then, the experimental data is analysed and compared to other experimental works and correlations. Different drag coefficient correlations for particles were selected and used to calculate the settling speed. These values were then compared to the experimental ones. The conclusion of this comparison lead to the development of a new correlation adapted to irregularly shaped drill-cuttings.

4.2 SETTLEMENT PARTICLE CHARACTERISTICS

4.2.1 Forces applied to the particle

4.2.1.1 Description of the settlement conditions

First of all, basic information needs to be presented about the settlement of a particle in a fluid. A 'particle' is a self-contained body with a maximum dimension between 0.5 microns and 10 cm separated from the surrounding medium by a recognisable interface. The material forming the particle can be termed the 'dispersed phase'. The particles whose dispersed phase is composed of solid matter are referred as 'solid particles'. 'Continuous phase' is referred as the medium surrounding the particles (Clift *et al* 1978).

In the present study, the attention was concentrated on solid particles which were free to move through the continuous phase (a static liquid in the present case) under the action of some body force such as gravity. The action from a cross-flow on the settlement of the particle was not the subject of this work. The overall aim of the next two chapters is to study the settlement of drill-cuttings of various shape and size in a static liquid such as water. First of all, the forces applied on the solid particle have to be assessed. They are the following:

- the gravity force;
- the buoyancy force, and;
- the drag force.

The total drag force consists of friction drag and pressure drag, and depending on the shape of the particle, one can be more important than the other. For the following sections, it is the total drag which is dealt with.

4.2.1.2 Equations for the forces

In the present work, no detailed study has been done on the boundary layer of the particle. If Newton's second law is applied to the system, the following equation is obtained:

$$m\frac{dv}{dt} = F_G - F_B - F_D$$

When the terminal velocity is reached:

$$\frac{dv}{dt} = 0 \Rightarrow F_D = F_G - F_B$$

The equilibrium of forces was simplified to the following equation (Naik 1996):

Drag force (F_D) = Gravitational force (F_G) - Buoyancy force (F_B)

The following diagram illustrates this concept (see Figure 4.1). The points of application and the size of the arrows representing the forces are not related to scale.

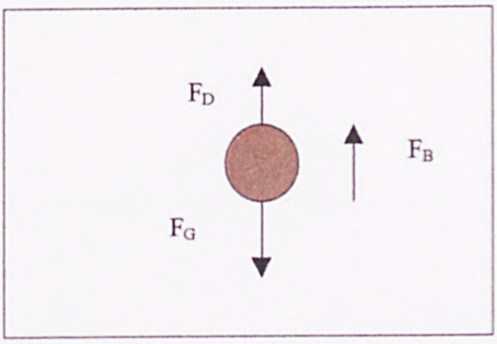


Figure 4.1: The forces applied to a particle (Naik 1996).

The drag force (see Figure 4.1) is the component of the resultant force exerted by a fluid on a body parallel to the relative motion of the fluid (in the present case, the particle is settling vertically downwards):

$$F_D = C_D \frac{1}{2} \rho_f v_p^2 A_p$$

$$F_G = m_p\, g = \rho_p\, V_p\, g$$

$$F_B = m_f\, g = \rho_f\, V_p\, g$$

(Giles *et al* 1994)

More detailed equations for the particle transport are given in section 5.2.2.

4.2.1.3 Equations for important parameters

In the previous sub-section, the equations for the forces were presented in a simple form. More information needs to be determined about the particle in order to study its settlement: the Reynolds number (R_{ep}) and the drag coefficient (C_D).
The surface area and volume of a sphere can be written as follows:

$$A_p = \frac{\pi d_p^2}{4}$$

$$V_p = \frac{\pi d_p^3}{6}$$

Therefore, the settling velocity of a sphere can be written as:

$$v_p = \left[\frac{4(\rho_p - \rho_f)d_p g}{3C_D\rho_f}\right]^{1/2}$$

then the drag coefficient of a sphere is:

$$C_D = \frac{4(\rho_p - \rho_f)d_p g}{3\rho_f v_p^2}$$

or more generally:

$C_D = f\,(R_{ep}$, shape factor)

with the Reynolds number of the particle being equal to:

$$R_{ep} = \frac{v_p d_p \rho_f}{\mu_f}$$

It has to be noted that the R_{ep} is in fact a function of the relative speed between the fluid and the particle (v_{rel}). However, in the present case, the fluid is static, therefore: $v_{rel} = v_p$.

The shape factor can be represented by the true sphericity (defined by Wadell 1932 and 1933):

$$\psi_p = \frac{A_{eq}}{A_p}$$

(A_{eq}: surface area of a sphere with the same volume as the particle)
More information about the drag coefficient and settling speed of irregularly shaped particles are presented in sections 4.3.1 and 4.3.2.

These equations were used in the analysis described in the next sections. The effect of non-sphericity on slip velocity is determined by evaluating the relevant drag coefficient at a given sphericity (using various methods), and then substituting these into the equatin for the settling speed given previously. The present study also concentrates on the available information on settling speeds for irregularly shaped particles and on drag coefficient for different shape and size of particles.

4.2.1.4 Characteristics of the present particles

In order to calculate any properties related to the analysis of the settlement of the drill-cuttings, several characteristics need to be known. For the particles used in this present study, the following characteristics were known:

- the particle size (the one corresponding to the settling speed);
- the density;
- the sphericity, and;
- the experimental settling speed.

Therefore, at this stage, all the required characteristics of the particles were known. They are summarised in Table 4.1.

Particle	Size	Density	Shape	Sphericity	Vexp
(No)	(m)	(kg/m3)	(n/a)	(n/a)	(m/s)
1	0.009525	2212.39	s	1	0.548
2	0.003175	2261.9	s	1	0.303
3	0.00675	2390	f	0.5	0.131
4	0.00675	2390	f/r	0.4	0.165
5	0.003675	2390	f/r	0.4	0.075
6	0.003675	2390	f	0.5	0.121
7	0.003675	2390	f	0.5	0.149
8	0.002675	2390	f/r	0.4	0.096
9	0.002675	2390	f	0.5	0.134
10	0.002675	2390	f	0.5	0.118
11	0.002675	2390	a/r	0.8	0.186
12	0.002675	2390	a/f	0.6	0.157
13	0.0015	2390	f/r	0.4	0.063
14	0.0015	2390	f	0.5	0.100
15	0.0015	2390	a/r	0.8	0.135
16	0.0015	2390	a/f	0.6	0.123
17	0.000925	2390	f/r	0.4	0.047
18	0.000925	2390	f	0.5	0.085
19	0.000925	2390	f	0.5	0.071
20	0.000925	2390	a/r	0.8	0.088
21	0.000925	2390	a/f	0.6	0.078
22	0.000675	2390	r	0.9	0.052
23	0.000675	2390	r	0.9	0.035
24	0.000675	2390	r	0.9	0.071
25	0.000675	2390	r	0.9	0.053
26	0.000675	2390	r	0.9	0.045
27	0.000325	2390	r	0.9	0.039
28	0.000325	2390	r	0.9	0.040
29	0.000325	2390	r	0.9	0.031
30	0.000325	2390	r	0.9	0.033
31	0.00012	2390	r	0.9	0.009
32	0.00012	2390	r	0.9	0.011

Table 4.1: The characteristics of the drill-cuttings.

These characteristics are used in the next sections to validate the experimental values and other works. The Reynolds number, regime and drag coefficient for all these particles are given in the next section (Table 4.2). This information was also the base for the development of a new correlation for the drag coefficient.

4.2.2 Influence of particle and fluid characteristics on the particle settling speed

4.2.2.1 Particle characteristics

The particle characteristics of influence to the settlement are:

- size;
- shape, and;
- density.

For the same shape and density, the bigger the particle, the higher the settling speed. This is because the volume of and therefore the mass of the particle increases, causing a larger gravity force. For the same size and sphericity, if the density increases, then the settling speed also increases. Once again, the reason for this is a higher mass and therefore a higher gravity force.

For the same size and density, the higher the sphericity (i.e. the closer to 1), the faster the particle will settle. This is because the more spherical the particle is, the less drag it will experience (assuming of course that all the other characteristics stated in this section are also constant), and therefore the quicker it will fall.

The shape of a particle is of great influence to the settling speed for two main reasons:

- it significantly changes the value of the drag coefficient, and;
- it influences the orientation of the particle falling in the fluid.

The orientation of the particle in respect to the direction of the fluid motion can change dramatically the trajectory of the particle and its settling speed value. This is especially of concern for very flat particles, as a different orientation of the particle will give a totally different settling speed (Williams and Bruce 1951, and Peden *et al* 1987). The orientation of the particle depends on its general shape but also on the uniformity of that shape. It also depends on the homogeneity of the particle material, and on the uniformity of the surface roughness. All these parameters will influence the more likely orientation of the particle during its settlement, and also the frequency of changes of this orientation. Peden *et al* (1987) observed during their experiments that the particles orientation during settling was independent of its orientation at release in all flow regimes. According to him, the orientation and type of settling (swinging or stable) depends directly on the R_{ep}. Depending on the R_{ep}, the total drag force will be more influenced by the pressure drag force or the viscous (friction) drag.

According to Wadell (1934), as well as the R_{ep}, the roundness of corners and edges are of influence on the settlement of the particle, especially at turbulent regimes. Some miscellaneous factors can also be summarised as:

- the deformation of the particle (i.e. change in shape but not in volume);
- the rate of disaggregation and aggregation, or even any change in the particle structure and mass (due to biological, chemical or physical processes), and;
- the 'stickiness' of the particle (this is especially of concern for particles like oily drill-cuttings). The 'coating' on the surface will change the drag coefficient and also the response to particle concentration.

The particle concentration is also of importance in the settlement. It can cause what is called 'hindered settlement'. So a particle settling speed depends among other factors on the concentration but also on the distribution of this concentration of other particles in the fluid. This dependence arises from particle interactions caused by velocity distributions generated in the fluid surrounding each moving particle. Some research has been done on this subject, for example by Clift *et al* 1978, Lovell 1991 and Govier 1987. The influence of such conditions on the settling speed depends on:

- the distance between particles, and;
- the uniformity of these distances;
- the difference in the particles characteristics (in terms of size, density, shape but also attraction/repulsion properties to other particles).

4.2.2.2 Fluid characteristics

As far as the fluid is concerned, the main characteristics are its density and viscosity. The more viscous and dense the fluid is, the more drag is experienced by the particle in motion in the fluid. For the present study, water is the only fluid being tested experimentally and computationally, therefore the values were (Hughes 1967):

- density: ρ_f=999.13 kg.m^{-3}
- viscosity: μ_f=1.145.10^{-3} kg.m^{-3}

at 15 degrees Celsius.

There are other characteristics such as:

- the chemical properties;
- the total contents of other fine particles or bio-organisms, and;
- the motion of the fluid.

4.2.2.3 Selected parameters

As it can be seen from the previous paragraphs, there are a large number of factors affecting the settlement of a particle in a fluid. For the present study, the selected parameters taken into account were:

- a single solid particle falling in static water;
- the size of the particle (d_p);
- the sphericity of the particle (Ψ_p)
- the density of the particle (ρ_p) and of the fluid (ρ_f);
- the viscosity of the fluid (μ_f);
- the Reynolds number of the particle (R_{ep});
- the drag coefficient (C_D), and:
- the settling speed of the particle (v_p).

Any parameter not listed above has been neglected for the purpose of this study.

4.3 SETTLING SPEED AND DRAG COEFFICIENT

4.3.1 Available correlations for the drag coefficient

The following sections present the available drag correlation which can be applied to the presented analysis. Each drag correlation has different limitations of applications (for example, in terms of particle regime and shape). The drag coefficients presented below are 'classified' by shape and then R_{ep}. The equations are numbered for a clearer presentation of the selected options.

4.3.1.1 For any shape

For particles of any shape, the following semi-theoretical formula can be applied:

$$C_D = \frac{4d_p\Psi_p(\rho_p - \rho_f)g}{3\rho_f v_p^2} \qquad \text{No 1}$$

For perfect spheres, this formula becomes the formula presented earlier in secion 4.2.1.

4.3.1.2 For round particles

With the pseudo-theoretical equation of Rubey (1933), the following drag coefficient can be used for round particles at all Reynolds numbers:

$$C_D = \frac{24}{R_{ep}} + 2 \qquad \text{No 2}$$

Dallavalle (1943) also developed a drag coefficient for round particles at all Reynolds numbers:

$$C_D = \frac{24.4}{R_{ep}} + 0.4 \qquad \text{No 3}$$

4.3.1.3 For flat particles

In this paragraph, the drag coefficient given by Clift *et al* (1978) is considered and is distinguished for two sorts of flat particles: disks, and long cylinders.

- For disks:

if $R_{ep} \leq 0.01$, $$C_D = \left(\frac{64}{\pi} R_{ep}\right)\left(1 + \frac{R_{ep}}{2\pi}\right)$$ No 4

if $0.01 < R_{ep} \leq 1.5$, $$C_D = \left(\frac{64}{\pi} R_{ep}\right)\left(1 + 10^{x}\right)$$ No 5

where $x = -0.883 + 0.906 \log_{10} R_{ep} - 0.025(\log_{10} R_{ep})^2$

if $1.5 < R_{ep} \leq 133$, $$C_D = \left(\frac{64}{\pi} R_{ep}\right)(1 + 0.138 R_{ep}^{0.792})$$ No 6

if $R_{ep} > 133$, $$C_D = 1.17$$ No 7

- For long cylinders:

if $0.1 < R_{ep} \leq 5$, $$C_D = C_D'(1 + 0.147 R_{ep}^{0.82})$$ No8

if $5 < R_{ep} \leq 40$, $$C_D = C_D'(1 + 0.227 R_{ep}^{0.55})$$ No9

if $40 < R_{ep} \leq 400$, $$C_D = C_D'(1 + 0.0838 R_{ep}^{0.82})$$ No10

where $C_D' = 9.689 R_{ep}^{-0.78}$

4.3.1.4 Selected correlations

For each particle used in the settling experiments, two drag coefficients (C_{D1} and C_{D2}) were selected from the presented correlations. The selection was done as a function of shape and regime (i.e. value of the R_{ep}). The values are summarised in the following table:

Particle	Size	Density	Shape	Sphericity	R_{ep}	C_D	C_{D1}	C_{D2}	Regime
(No)	(m)	(kg/m3)	(n/a)	(n/a)	(n/a)	(No)	(n/a)	(n/a)	(n/a)
1	0.009525	2212.39	s	1	4555	2,3	2.01	0.41	T
2	0.003175	2261.9	s	1	839	2,3	2.03	0.43	T
3	0.004	2390	f	0.5	457	1,7	2.12	1.17	T
4	0.004	2390	f/r	0.7	576	1,10	1.87	1.12	T
5	0.00335	2390	f/r	0.7	219	1,10	7.59	1.15	T
6	0.00335	2390	f	0.5	354	1,7	2.08	1.17	T
7	0.00335	2390	f	0.5	436	1,7	1.37	1.17	T
8	0.002	2390	f/r	0.7	168	1,10	2.77	1.17	T
9	0.002	2390	f	0.5	234	1,7	1.01	1.17	T
10	0.002	2390	f	0.5	206	1,7	1.31	1.17	T
11	0.002	2390	a/r	0.8	325	1,7	0.84	1.17	T
12	0.002	2390	a/f	0.6	274	1,10	0.89	1.14	T
13	0.001	2390	f/r	0.7	55	1,10	3.21	1.38	TR
14	0.001	2390	f	0.5	87	1,10	0.91	1.27	TR
15	0.001	2390	a/r	0.8	118	1,3	0.80	0.61	T
16	0.001	2390	a/f	0.6	107	1,10	0.72	1.23	T
17	0.00085	2390	f/r	0.7	35	1,9	4.90	1.58	TR
18	0.00085	2390	f	0.5	63	1,10	1.07	1.34	TR
19	0.00085	2390	f	0.5	53	1,10	1.54	1.39	TR
20	0.00085	2390	a/r	0.8	65	1,3	1.60	0.77	TR
21	0.00085	2390	a/f	0.6	58	1,10	1.53	1.36	TR
22	0.0005	2390	r	0.9	23	2,3	3.06	1.48	TR
23	0.0005	2390	r	0.9	15	2,3	3.57	2.00	TR
24	0.0005	2390	r	0.9	31	2,3	2.77	1.19	TR
25	0.0005	2390	r	0.9	23	2,3	3.04	1.46	TR
26	0.0005	2390	r	0.9	20	2,3	3.22	1.64	TR
27	0.00015	2390	r	0.9	5	2,3	6.70	5.18	L
28	0.00015	2390	r	0.9	5	2,3	6.58	5.06	L
29	0.00015	2390	r	0.9	4	2,3	7.91	6.41	L
30	0.00015	2390	r	0.9	4	2,3	7.56	6.05	L
31	0.00009	2390	r	0.9	1	2,3	35.96	34.92	L
32	0.00009	2390	r	0.9	1	2,3	29.78	28.64	L

Table 4.2: The different drag coefficients for each particle.

The shape is coded in the same way as in Chapter.3 (a: angular, f: flat and r: round and combinations). The sphericity is the one determined as in section 3.3.3. The Reynolds number of the particle was calculated using the value of the experimental settling speed (see section 4.2.1.4). The two numbers under 'C_D' correspond to the number of the two equations selected for a specific particle. The first number is either 1 or 2, meaning that for spheres and round particles, equation No 1 was used, whereas for other shaped particles, the equation No 2 was preferred. The second number represents more specific correlations. For flat particles, the equation for disks was preferred for Re > 200. For particles with Re < 200, equation No 6 would give unrealistic values, so in this case, the correlation for cylinders (No 10) was used. For f/r and a/f, the equations for long cylinders (No 8, 9 and 10) again were thought to be more appropriate. 'C_{D1}' and 'C_{D2}' represent respectively the value of the C_D for the first and second choice of correlations. Finally, the regime for the particle is given as:

- laminar (T): $0 < R_{ep} < 10$;
- transitional (TR): $10 < R_{ep} < 100$, and;
- turbulent (L): $R_{ep} > 100$.

All these values and equations were also used for the computational simulation presented in Chapter.5. However, some values were directly used to compare experimental settling speeds with other values in the next section.

4.3.2 Experimental works on particle settling speed

4.3.2.1 Present experimental work

First of all, all the experimental values for the settling speed values from the present study were gathered. It is reminded that any experimental value was the average over at least 6 values for each size. Five samples had been through a reasonable number of settling experiments to be of interest:

- No 50: a mixture of clay and sandstone with flat (F) big particles and round (R) small particles;
- No 51 and 52: soft clay with particles of the very specific shape 'flat PDC';
- No 36: contains claystone and sandstone with angular (A) and flat (F) particles;
- No 25: sandstone with angular (A) and round (R) particles.

All these samples were drilled with WBM apart from No 36 which was drilled with OBM. Results from these settling experiments and can be viewed in Figure 4.2.

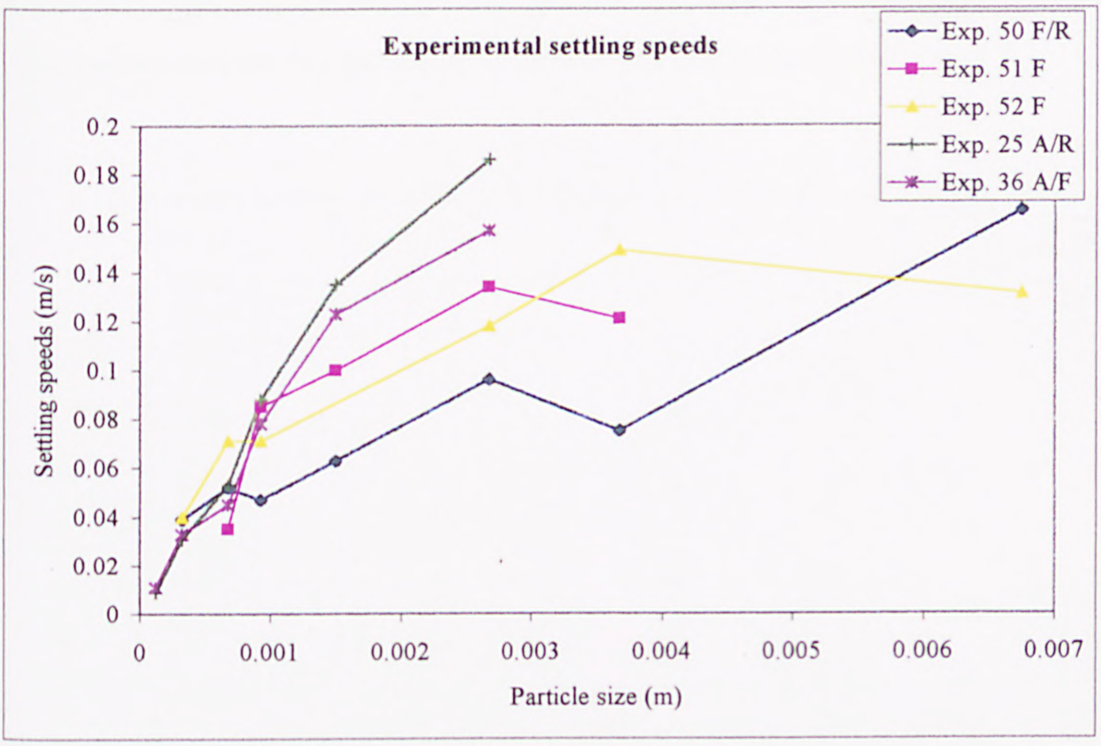


Figure 4.2: Experimental settling speeds.

On these graphs, it can be seen that the logics presented in section 4.1.2 were respected:

- the bigger the particles, the quicker they are;
- the flatter the particles, the slowest. Therefore, the angular particles are quicker than the flat ones, and;
- the shape of the particles is more important for bigger particles than for small ones (this can be observed because of the divergence of values after a certain size).

The first interesting comparison conducted was with 'theoretical' values. The simple equation presented in section 4.2.1.2 was used:

$$v_{th} = \left[\frac{4(\rho_p - \rho_f)d_p g}{3C_D\rho_f}\right]^{1/2}$$

Values for v_{th} were first calculated using a constant value for C_D: 0.44 (most of the particles were either in transitional or turbulent regime). Moreover, in order to see the difference for each shape and drag coefficients, values for the two selected C_D (see

Table 4.2) were also computed in the equation. The values for v_{th1} were calculated with C_{D1} and the ones for v_{th2} with C_{D2}. The overall results are shown in Figure 4.3.

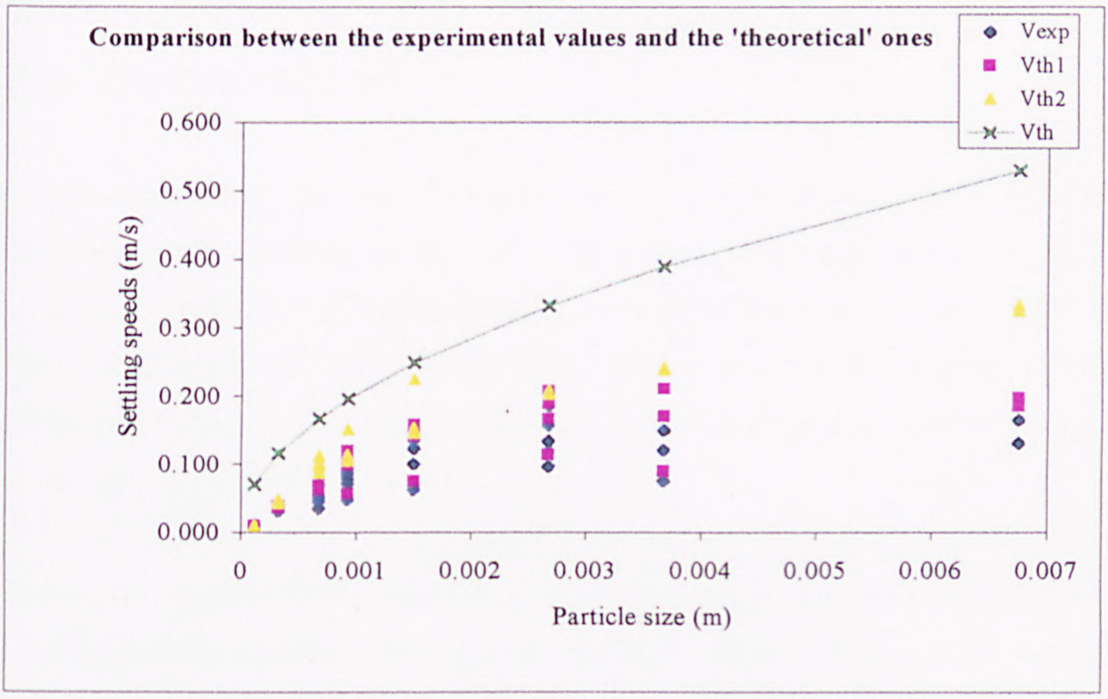


Figure 4.3: Comparison between experimental settling speeds and theoretical values.

Because the volume of the cuttings was not known, the equivalent spheres (the sphere of equivalent volume) could not be used. Instead, spheres with an equivalent diameter were used. A sphere has a maximum volume for a given diameter. Therefore, the fact to use spheres of equivalent diameter rather than equivalent volume means that these spheres are much bigger than the particles they represent in the equation. These spheres, with a maximum sphericity and a volume (and therefore mass) bigger than the actual particles, will fall faster. That is why, on this graph, it was expected to see that the theoretical values for a sphere of a same diameter would be far above the experimental values.

The other interesting fact is that the two selected theoretical values (v_{th1} for C_{D1} and v_{th2} for C_{D2}) follow more closely the experimental curves than the Vth curve for spheres. This was an expected phenomenon of course, but the results were amazing for C_{D1}. They seem to respect the changes in size and shape very closely. This means that the selected correlations for the C_D of particles were well adapted to the shape and Re of the particles. However, the agreement between values could be better with a single correlation which can include the sphericity of the particle. This problem is dealt with in section 4.4.

4.3.2.2 Other experimental works

In order to 'validate' the present experimental data, other experimental works were selected from the literature review. They represent various works from: Fang 1992, Mamak 1964 and Gibbs 1971. Other works by Zeidler 1972, Sample 1977 and 1978, Delft 1993, Hopkin 1967 and Hussaini 1983 were reviewed. However, most of these publications did not contain a large range of sizes for comparison or would not contain relevant data for comparison.

For example, Hussaini (1983) conducted experiments to determine the settling speed of real drill-cuttings in various drilling fluids. He only used two sizes, and the particles were drilled Carthage marble cuttings. Researchers from Delft (1993) conducted experiments to define the size and settling speed of real offshore drill-cuttings. They had ten samples from North Sea offshore installations. However, those cuttings were treated using different methods for cleaning the mud off them. The aim of their experiments was to compare the different methods of treatment and their impact on cuttings characteristics. Their report is very interesting and full of useful information (especially on flocculation and aggregation of the cuttings) for someone who is studying the impact of drill-cuttings discharge on the environment.

Gibbs *et al* (1971) carried out a large number of experiments with spheres of various diameters. He varied the temperature of the water (from 10°C to 20°C) and the density of particles (from 2.5 $kg.m^{-3}$ to 5.0 $kg.m^{-3}$). He also created data for different salinities of water. Two of his sets of data were used for comparison: one with the density equal to 2.65 $kg.m^{-3}$ and the other one with 2.50 $kg.m^{-3}$.

The next work for comparison was done by Mamak (1964) on quartz particles. The specific gravity of his particles was equal to 2.65 which is higher than that of the particles used for the present particles. He used odd-shaped particles which he dropped in water at 20°C.

Finally, data from Fang (1992) were compared to the present ones. Even if the available data from the publication was not very large, this work was chosen as it was one of the latest ones. Fang used four different sizes of particles with a density of 2.65 $kg.m^{-3}$. He let the particles settle in a column of water and also monitored their settling pattern (i.e. stable or swinging).

When the diameters of the particles were not the same as the ones used for the present study, values were interpolated using the linear interpolation method (see section 3.4.1). All the values were then compared and the results of this comparison are presented in the next section.

4.3.2.3 Comparison

As stated in the previous section, the present experimental data was compared with the works from: Fang 1992, Mamak 1964 and Gibbs 1971. The following graph represents all the results together.

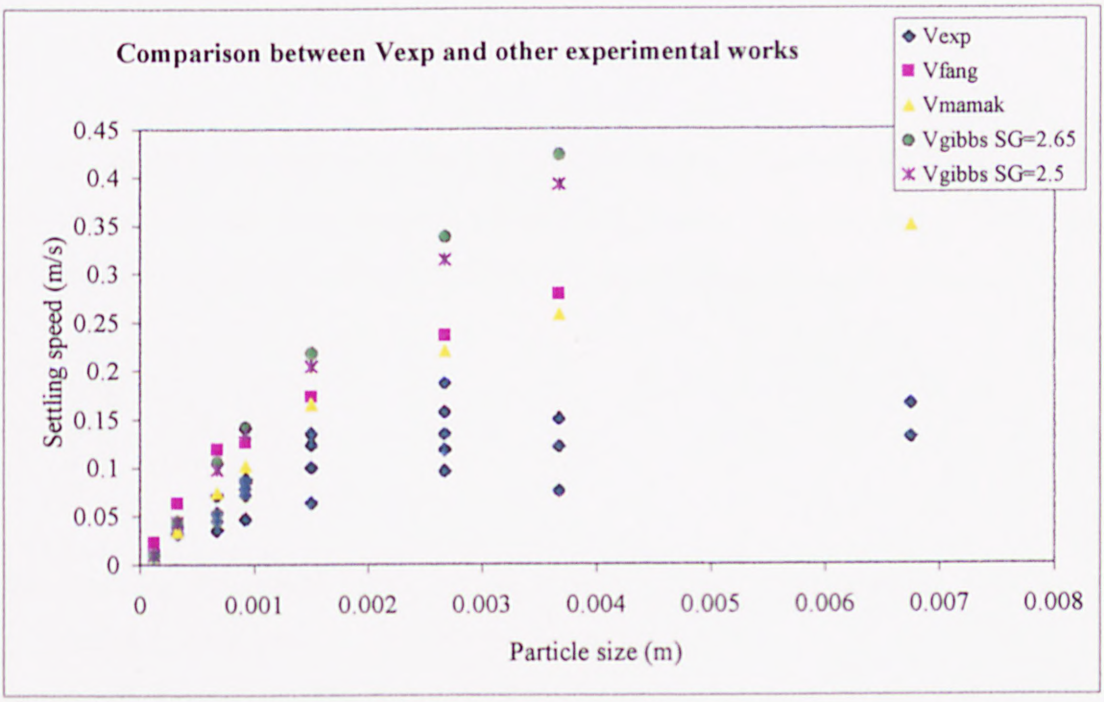


Figure 4.4: Comparison between the experimental values and other works.

On the graph, it is observed that all the other works overestimate the present data. It was expected as the sphericity of the particles used by other researchers were more regular and close to 1. Once again, it is noticed that values diverge greatly after a size of 0.0015 m. All the values for very small particles (0.00012 and 0.000325) are very similar. It was surprising to see Gibbs' data were the furthest from the present data. In effect, his data came from particles with a similar density (2.5) as the present particles (2.39). This explained by the fact that he probably used 'perfect' spheres. Mamak's and Fang's data are very close to each other and also the closest to the present data. The reason for these two statements is that they both used odd-shaped particles. It can also be noticed by looking at Figure 4.3 as well that all the other experimental works are much closer to the 'theoretical' values.

This comparison was very interesting and showed that the present data was consistent with other experimental works. It also showed the difficulty to find similar works when dealing with specific shape and density.

4.3.3 Correlations for particle settling speed

4.3.3.1 Available correlations for v_p

The experimental data were also compared to correlations. From the literature review, three correlations were selected from Chien 1972, Moore 1986 and Rubey 1933. The first correlation which was compared to the experimental values was by Chien (1972):

$$v_p = 86.5\sqrt{\left[d_p\left(\frac{\rho_p}{\rho_f}-1\right)\right]}$$

In this equation, v_p is given in ft/min if d_p is in inches and the specific weights are in ppg. To suit S.I. units, Chien's equation was modified as follows:

$$v_p = 2.757\sqrt{\left[d_p\left(\frac{\rho_p}{\rho_f}-1\right)\right]}$$

where v_p is in m/sec if d_p is in metres and the specific weights are either in ppg or SG (because it is a ratio, in this case, the two units give an equivalent result). According to Chien (1972), this correlation is valid for 'normal drilling fluids and cuttings size' (which means drilling fluids with no abnormally high viscosity and cuttings with a size between 0.3 and 1.6 cms).

The second correlation was by Moore (1986). According to Moore, the following equation should be used for routine solutions in problems related to drilling engineering:

$$v_p = 0.154 \frac{d_p \left[g(\rho_p - \rho_f)\right]^{0.667}}{(\rho_f \mu_f)^{0.333}}$$

In this equation, d_p can represent the sieve diameter of the particle.

The last correlation used for the comparison is by Rubey (1933). It is valid for perfect spheres:

$$v_p = \frac{\sqrt{\frac{16}{3} g\rho_f(\rho_p - \rho_f) r^3 + 144\eta^2}}{\rho_f r} \frac{-12}{\rho_f r}$$

with r being equal to half the diameter of the particle.

4.3.3.2 Comparison with present data

As stated in the previous section, the present data was compared to correlations from Chien 1972, Moore 1986 and Rubey 1933. All the values were computed and plotted on the same graph. Figure 4.5.

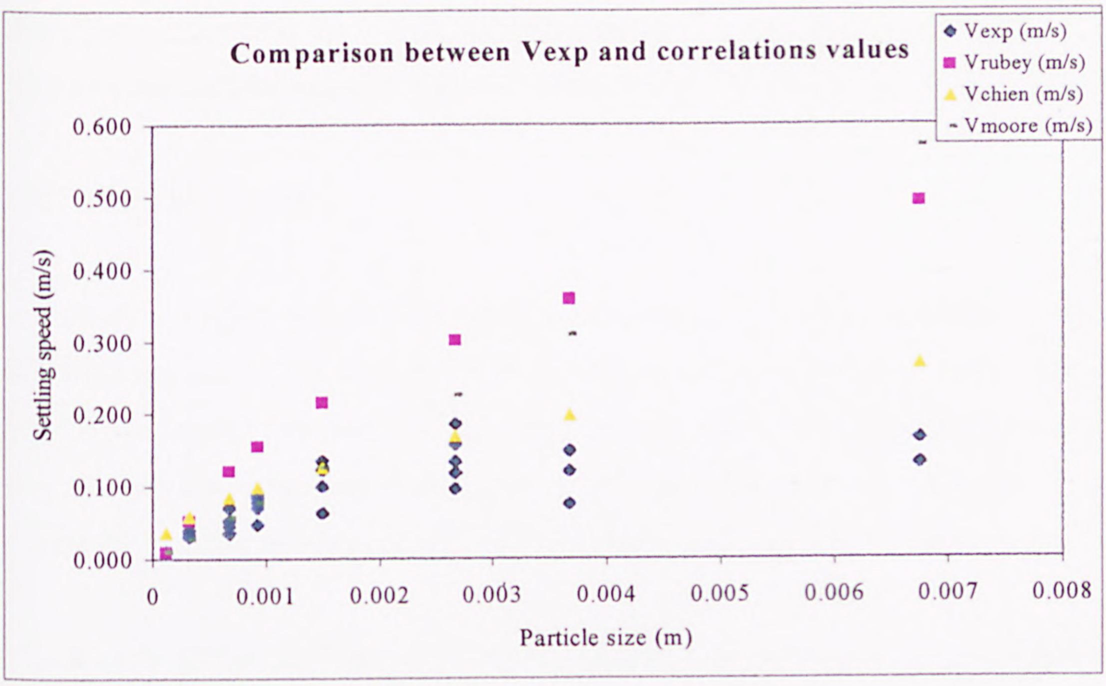


Figure 4.5: Comparison between the experimental values and correlations.

From these graphs, it can be noted that Chien's correlation values are generally in good agreement with experimental values. Nevertheless, they tend to be better for flat particles. They overestimate all the values for small particles ($d_p < 0.00085$ m) and also the ones for every angular particles. It is also noticed that this graph is very similar than the one for the comparison with experimental works. The same general comments apply to both graphs.

4.4 A NEW CORRELATION FOR THE DRAG COEFFICIENT

4.4.1 Introduction

In the previous sections, the present experimental data was compared to other experimental data and correlations values. A combination of drag coefficients was selected to calculate the settling speed of irregularly shaped cuttings. Two different drag coefficients were determined for every particle. The results of these calculations were plotted against the experimental values. Values from C_{D1} proved to be the closest to experimental values. However, this comparison showed the need for a more adapted drag correlation. This new correlation should be valid for drill-cuttings of any shape and size. The next section deals with the development of a new drag coefficient based on experimental data for irregularly shaped particles and well-known formulae for spheres.

4.4.2 Available graphs

As stated in the previous sections, drag coefficients of particles are dependent on the Reynolds number of the particle at low and intermediate velocities. However, they are mostly independent from them at high velocities (see Figure 4.6). It can be noted even if it is not the case of the present study that, at very high velocities, the drag coefficient is related to the Mach number (ratio of the velocity of the fluid to the speed of sound).

The drag coefficient can also vary with the roughness of the surface of the particle, but this factor has not been taken into account in this study. As far as the present work is concerned, the drag coefficient only varies under the influence of the R_{ep} and the sphericity of that particle (see Figure 4.6). As stated in the previous sections, one way to determine the drag coefficient for a particle is to use some equations developed by researchers. These equations can be empirical, theoretical or even pseudo-theoretical. Another way is to use graphs showing the relationship between C_D and R_{ep} for different sphericities. From the literature review, several graphs were found to express the relationship between R_{ep} and C_D. Some of them take into account the sphericity of the particles (Govier and Aziz 1982, Chien 1994 and Graf 1966) and others do not (for example, Fang 1992 and Bird *et al* 1960). One example is shown in Figure 4.6.

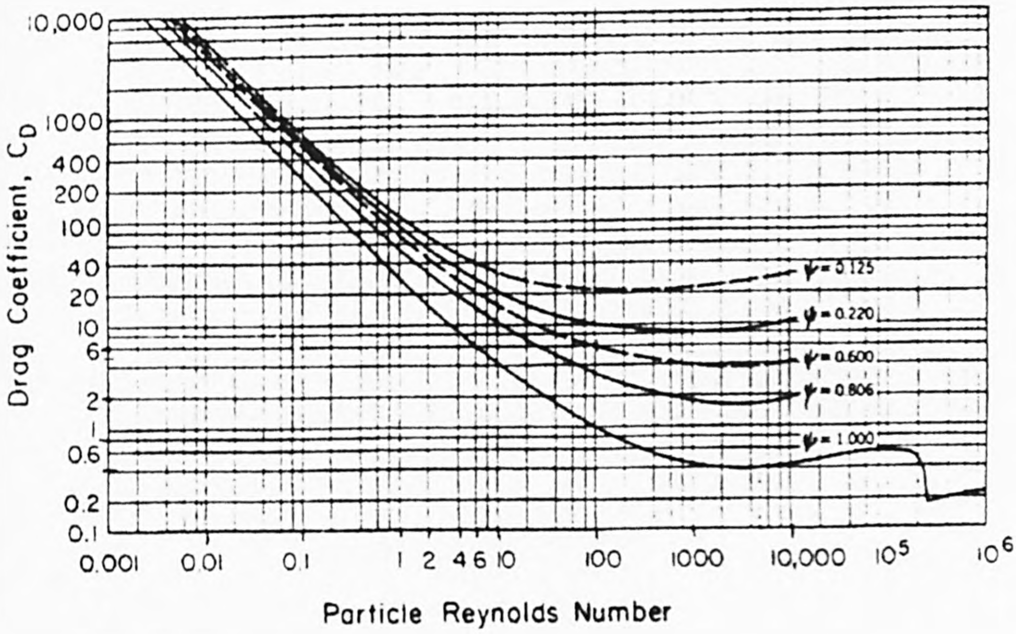


Figure 4.6: Relationship between the R_{ep}, sphericity and C_D of irregularly shaped particles (Govier and Aziz 1982).

On the graphs, it can be observed that C_D decreases when R_{ep} increases until a certain value for R_{ep}. After this threshold (which is about 100), the C_D becomes almost constant. Therefore, for turbulent regime, it is a good approximation to use a constant C_D. This constant value varies for every sphericity: the lower the sphericity, the higher the constant. This is perfectly logical as it means that there is more drag on an irregularly-shaped particle than on a spherical one. The aim of the next section is to show the development, analysis and validation of a new correlation for the C_D.

4.4.3 Present drag coefficient values

In order to develop the correlation, a graph representing the C_D versus the R_{ep} from experiments was firstly produced. The R_{ep} for every particle was calculated using the following equation:

$$R_{ep} = \frac{v_p d_p \rho_f}{\mu_f}$$

Then, the drag coefficient was calculated using the semi-theoretical formula:

$$C_D = \frac{4d_p \Psi_p (\rho_p - \rho_f) g}{3\rho_f v_p^2}$$

This formula was used to calculate the drag coefficient of the present particles. The experimental Reynolds numbers were first calculated using the experimental settling speeds. These values were then plotted on a graph which is presented below.

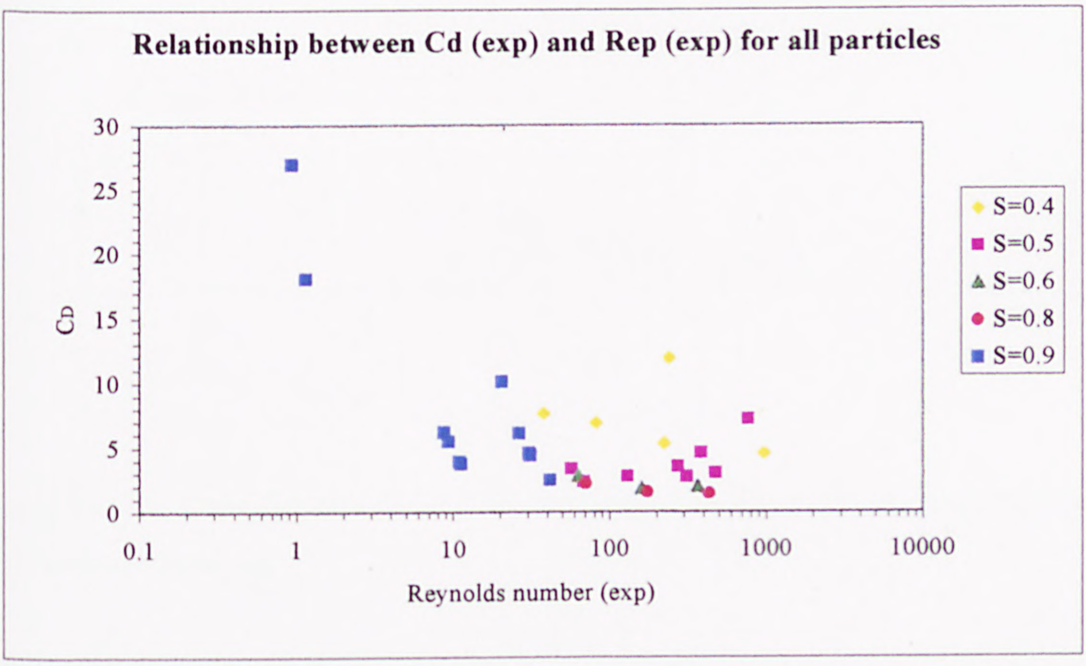


Figure 4.7: Experimental values for Reynolds number and drag coefficient of particles.

In Figure 4.7, it can be seen that the experimental values for C_D follow the general physical logics:

- for a same sphericity, the higher the R_{ep}, the lower the C_D, and;
- the C_D values are decreasing until a certain threshold for R_{ep}, after which they stay more or less constant, and;
- for the same R_{ep}, the higher the sphericity, the lower the C_D.

However, an 'outsider' is present with, a sphericity of 0.4, a C_D of 11.90 and a R_{ep} of 240.51. The reason for this might be an inaccurate assessment of the sphericity of that particle.

The experimental values were compared to the previously presented drag correlations values. The following Figure 4.8 shows the results of the comparison.

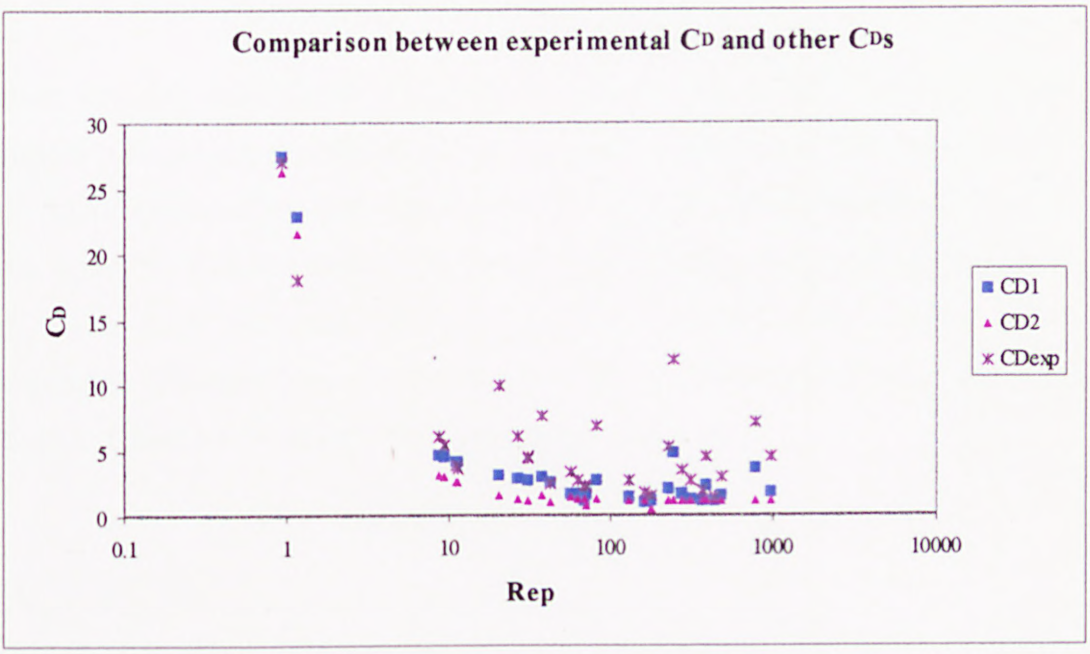


Figure 4.8: Comparison between the experimental values for C_D and R_{ep} and the correlations values.

As it can be observed on the graph, the values for C_{D1} and C_{D2} are in general lower than the experimental ones. This might be explained by the fact that the selected correlations were developed for more regularly shaped particles than the experimental ones. The experimental values are more disperse because they represent real particles with very different shapes.

4.4.4 Development of the new correlation

In order to develop the new correlation for the drag coefficient, the experimental values were used for sphericities different than 1. In effect, no experimental data was available for spheres ($\Psi = 1$). It was therefore decided to use well-known correlations in order to calculate the C_D of spheres. Then, all the data was 'put together' for the fitting exercise. The well-known correlations were given by Bird *et al* (1960) and can be presented as follows:

- - for $0.01 \le R_{ep} \le 1$: $C_D = 24/R_{ep}$
- - for $2 \le R_{ep} \le 500$: $C_D = 18.5/R_{ep}^{3/5}$
- - for $500 \le R_{ep} \le 2x10^5$: $C_D = 0.44$

So, values were calculated for $\Psi = 1$ for the range $0.01 \le R_{ep} \le 2x10^5$. An Excel sheet was created with all the experimental and calculated values. Then, the Least Square Method (LSM) (presented in more detail in section 6.1.2.3) was used to find the best fit of every point. In order to change the variables of the selected equations, the 'tool Solver' within Excel was used. This was to find the values for the variables for a minimum error. Different forms of equations were tried to fit the experimental data. The same form as Chien's correlation (1994) proved to be the best:

$$C_D = \frac{a}{R_{ep}} + \frac{b}{e^{c\Psi}}$$

The values for a, b and c were changed by the Solver until the error was minimum. The following correlation was obtained:

$$C_D = \frac{24}{R_{ep}} + \frac{39.88}{e^{4.54\Psi}}$$

The average error was calculated using the deviation normalised by the mean square of the experimental values:

$$E = \frac{\Sigma(y_{fit} - y_{exp})^2}{\Sigma y_{exp}^2} * 100$$

For the new correlation, E = 0.0025% which was a very satisfying number. The reason why this number is so low is probably because a large amount of data came from the calculations for the spheres. They were 'easy' to model and added accuracy to the fitting. The new correlation was plotted using regularly incremented values for the R_{ep} and $0.1 \le \Psi \le 1.0$. The following Figure 4.9 shows the results.

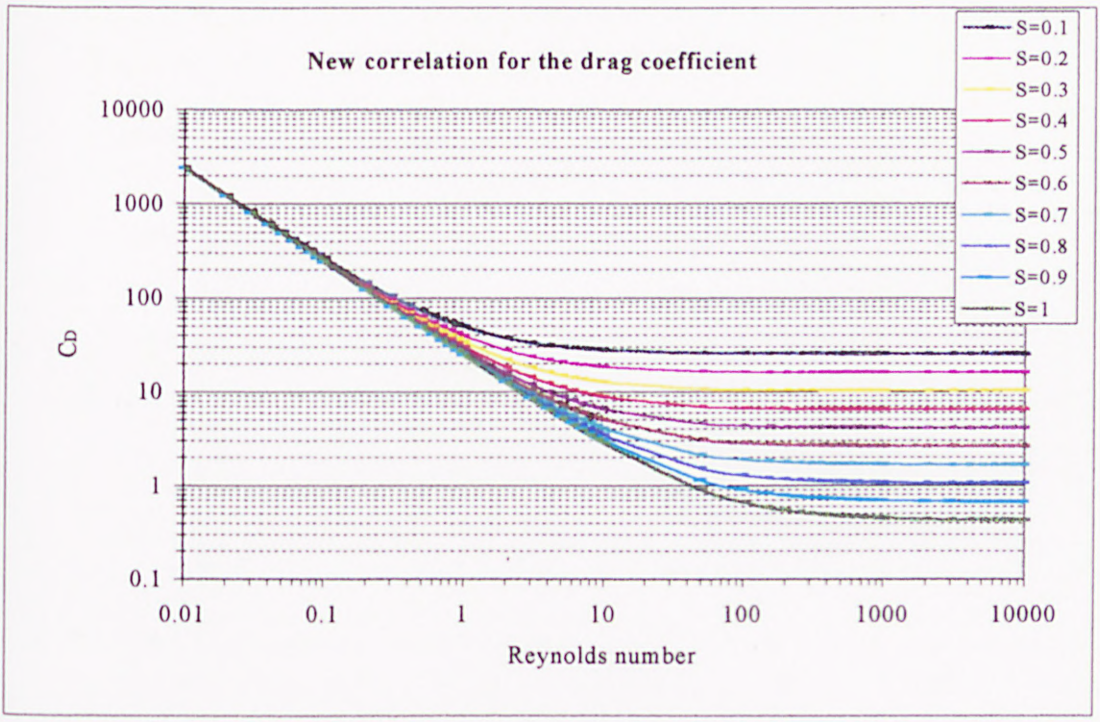


Figure 4.9: The new correlation for the drag coefficient.

The new correlation is analysed in the next section.

4.4.5 Analysis of the new correlation

An analysis of the new correlation was carried out. This analysis was to define the validity and limitations of this correlation. The only known correlation which could be compared to the new one was the one by Chien (1994). It was not possible to plot the two correlations on the same graph. Therefore, for Chien's correlation, the equation is given and a graph presented. Specific comparison is made between the two graphs.

Chien's equation is as follows:

$$C_D = \frac{30}{R_{ep}} + \frac{67.289}{e^{5.03\Psi}}$$

According to Chien, this correlation is valid for $0.2 \leq \Psi \leq 1.0$ and $0.001 \leq R_{ep} \leq 10^5$. This correlation was plotted using the same method as for the new correlation (see Figure 4.10).

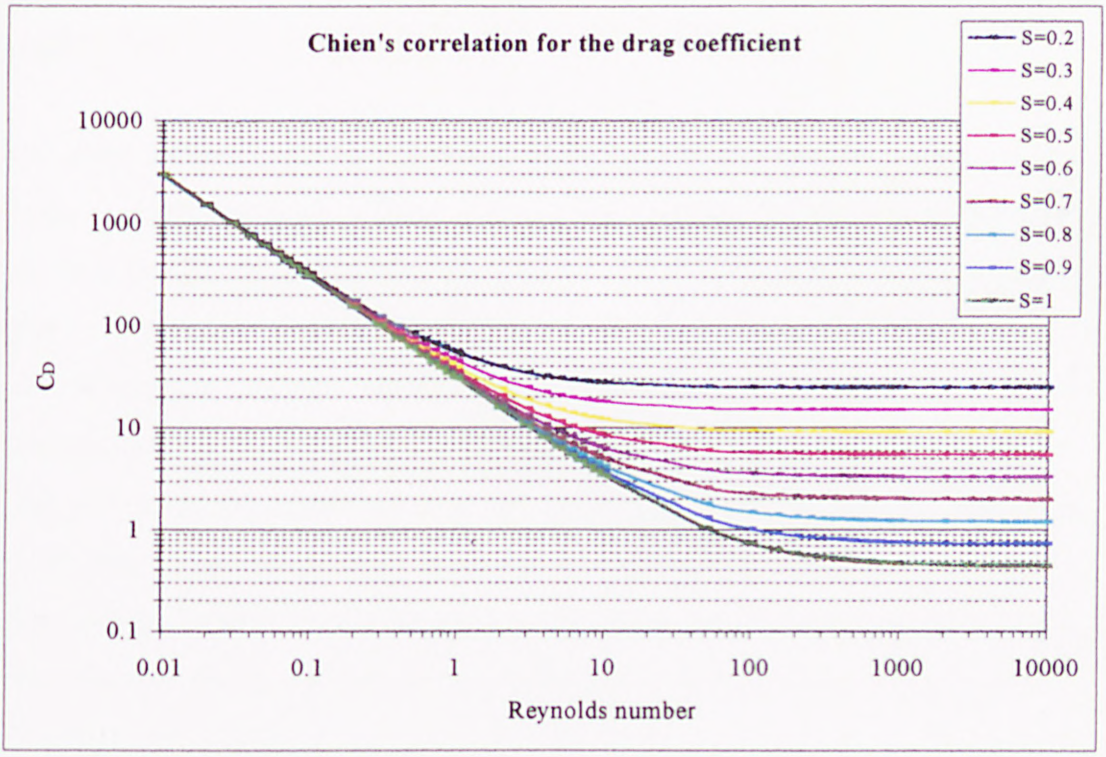


Figure 4.10: Chien's correlation for the drag coefficient.

A very strong similarity is observed between the two correlations. To develop this equation, Chien used data from other researchers'work (e.g. Hopkins 1967, Richards 1908, Moore 1986, and Zeidler 1972). Therefore, it was a very valuable to see that the new correlation (using independent data from those works) was so similar to Chien's. It was noticed for example that the new correlation has a higher 'constant' value for Ψ = 0.2 than Chien's correlation. Another interesting fact for the analysis is a = 24 in the new correlation. This value appeared naturally in the correlation. It means the first part of the new correlation can be related to Newton's law.

The graph was also compared to two available graphs found in the literature review (Govier and Aziz 1982 (see Figure 4.6) and Graf 1966). Similar features were found:

- the constant value for C_D is found earlier in the range of R_{ep} for low sphericities;
- all the curves reach their constant values after a R_{ep} higher than 500 (turbulent regime);
- for $\Psi = 1$, the common constant is comprised between $0.4 \leq C_D \leq 0.5$, and;

- the different curves (for different sphericities) always strongly diverge from R_{ep} higher than 5.

Some values for the C_D for specific values of R_{ep} (e.g. 1, 10. 100, 1000) were compared between the different graphs. They showed a good agreement between all the values. There were also dissimilarities between the new and Chien's correlations with the other graphs:

- the divergence between values happens earlier in the range of R_{ep} for the experimental graphs (as opposed to the correlations graphs);
- the curves for the experimental graphs are increasing again after R_{ep} higher than 1000, and;
- the average values for C_D at $R_{ep} = 0.01$ are between 2000 and 6000 for the experimental graphs and only between 2000 and 3000 for the correlations'graphs.

As a conclusion, it can be said that the new correlation is definitely valid for $0.1 \leq \Psi \leq 1.0$ and $0.01 \leq R_{ep} \leq 1000$. It can be applied to all solid particles of which the sphericity, density and settling speed (or Reynolds number) is known. This new correlation is also validated in the modelling exercise described in Chapter.5.

4.5 SUMMARY

In the previous sections, the settlement of particles in water was studied. The forces and parameters of influence were described. Several drag coefficients were selected to represent the drag of the present irregularly shaped particles. Present experimental data were compared to settling speeds calculated with those drag coefficients. They were also compared to other experimental works and to different correlations.

As a summary, it can be said that there was an obvious difficulty to find relevant data to compare with. There was also a vital need for a more adapted correlation for the drag coefficient. The new drag correlation is a useful tool to help the prediction of cuttings dispersion in water for example. It is important that, when dealing with drill-cuttings transport, the adequate drag correlation is applied. It is an advancement in knowledge to be able to use a drag coefficient based on experiments conducted on real drill-cuttings.

Chapter.5

THE MODELLING OF THE PARTICLE SETTLEMENT

5.1 BACKGROUND

5.1.1 Introduction

In Chapter.4, the analysis of the settlement of drill-cuttings in water was carried out. A new drag correlation valid for irregularly shaped particles was developed. In Chapter.5, computational tests are presented to validate the previous results by solving full equations for the particle settlement. The main objective of these tests was to compare the experimental results and other works with computational values. A Computational Fluid Dynamics (CFD) commercial package was used as a tool to solve more complex equations than in Chapter.4. There is no claim in this work to make any advancement in CFD techniques. The package was simply an available tool to model the particles settlement in an iterative manner. Similar results could have been produced with other computational tools such as Mathcad. The forces applied on the particles were presented in Chapter.4. The modelling exercise did not take into account more forces than the presented ones. The commercial package only allowed solving the equilibrium of forces with more complexity. The equations presented in a later section (section 5.2.2) describe the transport of solid particles.

The CFD package was also a very useful support tool for comparing the selected drag correlations with the default and new correlations. The drag coefficients were easily introduced in the system and were part of the iterative system to calculate the settling speed of the cutting. The CFD package also provided very good quality output in an ideal format. Chapter.5 presents briefly the structure of a CFD package and the tests carried out. The results are then analysed and conclusions are drawn.

5.1.2 Computational Fluid Dynamics

CFD is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation. The technique is very powerful and spans a wide range of industrial and non-industrial application areas. CFD codes are structured around the numerical algorithms that can tackle fluid flow problems. In order to provide easy access to their solver power all commercial CFD packages include sophisticated user interfaces to input problem parameters and to examine the results. Hence all codes contain three main elements:

- a pre-processor;
- a solver, and;
- a post-processor.

Briefly, the pre-processor consists of the input of a flow problem to a CFD program by means of an operator-friendly interface and the subsequent transformations of this input into a form suitable for use by the solver. At this stage, the geometry is created as well as the grid and the inlet and outlet are defined. The solution to a flow problem (velocity, pressure, temperature etc.) is defined at nodes inside each cell. The accuracy of a CFD solution is governed by the number of cells in the grid. In general, the larger the number of cells the better the solution accuracy. Both the accuracy of a solution and its cost in terms of necessary computer hardware and calculation time are dependent on the fineness of the grid.

Then, for the solver, there are three distinct streams of numerical solution techniques: finite difference, finite element and spectral methods. Here, discretisation and solution of the algebraic equations take place. The main differences between the three separate streams are associated with the way in which the flow variables are approximated and with the discretisation processes. The most commonly used method (the one used by the present package) is the finite volume method.

Finally, as in pre-processing a huge amount of development work has recently taken place in the post-processing field. Owing to the increased popularity of engineering workstations, many of which have outstanding graphics capabilities, the leading CFD packages are now equipped with versatile data visualisation tools. More recently, these facilities may also include animation for dynamic result display and in addition to graphics, all codes have data export facilities for further manipulation external to the code. As far as the post-processor is concerned, the graphics capabilities of CFD codes have revolutionised the communication of ideas to the non-specialist. The presented concepts are summarised in Figure 5.1.

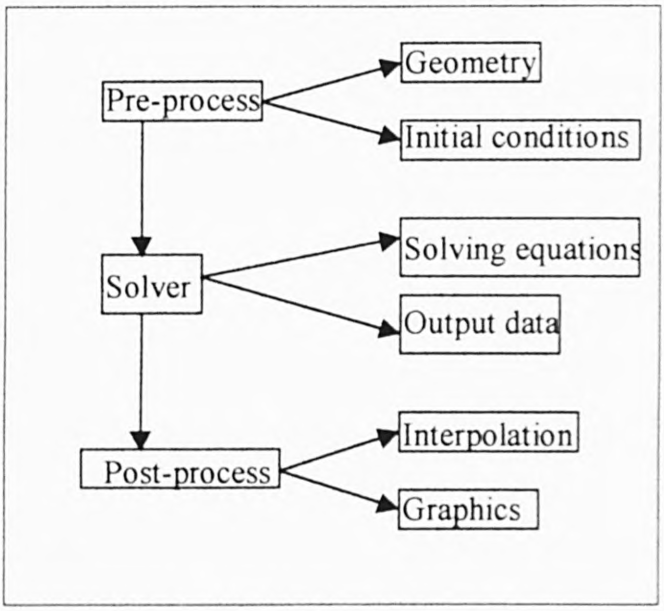


Figure 5.1: The structure of a CFD package.

The process of solving a problem with a CFD tool has to respect the order shown in Figure 5.1. First the geometry file is created giving the physical boundaries of the problem. Then the initial conditions are set up, for example in a 'command file'. This command file includes the conditions for the problem but also how it will be solved. Finally, the results are monitored in an output file and can be manipulated using the post-processor.

In solving fluid flow problems, one needs to be aware that the underlying physics is complex and the results generated by a CFD code are at best as good as the physics (and chemistry) embedded in it and at worst as good as its operator (Versteeg *et al* 1995).

5.1.3 Objectives of the present modelling exercise

The main and final objective of the present modelling exercise was to validate the experimental values for the settling speeds of real drill-cuttings using a computational tool. At the same time, the opportunity was taken to also validate some of the available correlations for the settling velocities and drag coefficient for odd-shaped particles. Therefore the first step was to use the experimental calibration tests made with Teflon spheres (see section 3.5.3), and compare the results between the laboratory experiments, the theoretical values and the CFD values. Then, if good agreement was found between the values, tests on different sizes and shape could be carried out. In order to do so, the work was divided into different steps, some of them inherent to the use of a CFD tool to:

- build the appropriate geometry and adapt it to each different tests;
- set up initial conditions flexible enough for every test;
- describe the transport of solid particles in static water;
- introduce various equations for the drag coefficient (including the new one) in the solver;
- run the test and check the output file for convergence and values for the settling speed;
- visualise the results for the final check, and;
- compare all the results.

5.2 DEVELOPMENT OF THE MODEL

5.2.1 Initial set up

5.2.1.1 The geometry

The geometry is a very delicate part of the modelling. The accuracy, time of solving and the quality of the model depend partially on it. A good model starts with a well-designed geometry. A suitable geometry is expected to:

- represent the reality of the studied problem;
- have a fine enough mesh to reach a good accuracy in the solved variables;

- have a reasonable amount of cells so the solving does not take a ridiculous time to process, and;
- represent a large enough domain so all the needed physical phenomenon can be observed.

When a geometry is created, two types of domains are included: the physical domain and the computational domain. The physical space is the one created by the user giving dimensions in S.I. units for example. Usually, this is done using the pre-processor of the modelling package; in the present case, this was done using 'Build' within CFX 4.2. The user defines the points, curves, surfaces and solids which will form the final geometry. The patches (inlets, outlets, walls, pressure boundaries... etc) and the mesh for the geometry have to be defined at this stage. Each pre-processor offers different ranges of possibilities to go through all these processes. All of them are more and more 'automised' and user-friendly, and can also import geometries from packages like 'Autocad' or 'Pro-Engineer' for example. These are very useful for important and complicated geometries. In the case of the present study, the geometry was relatively small and very simple.

One of the first tasks in creating a new geometry is to define the boundary conditions. These can be described in terms of mathematical equations, but also in terms of 'patches' specifications in the pre-processor. In the present geometry, the following patches were imposed and are shown in Figure 5.2.

- an inlet;
- an outlet, and;
- four solid walls.

The inlet defines the surface of the fluid domain where the fluid comes in; while the outlet defines the surface where the fluid goes out. In the present geometry, the other patches are solid walls, which means that, the fluid can get through those surfaces. Moreover, the speed of any phase very close to those walls is, as a default in CFX 4.2, equal to zero.

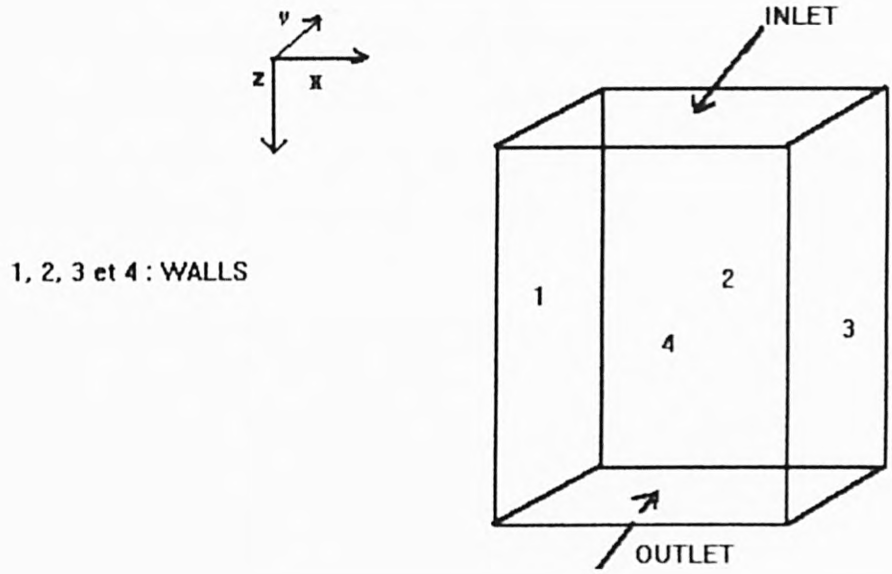


Figure 5.2: The different patches of the geometry.

First of all, the geometry was created using the original water tank dimensions (0.3/ 0.4/ 1.5 meters). Because of the great size of the domain and the limitations in the number of cells that the system can handle, the mesh had to be very coarse as a first approach. Progressively, the dimensions of the physical space in which the falling particle was modelled were reduced. As the terminal speed was the main interest of the tests, the domain was reduced to the minimum length where it could be observed. This was done so the mesh could be fine enough to ensure the accuracy of the given settling speeds. After many tests, it was clear that the terminal speed was reached very quickly. Three different geometries were adopted depending on the size of the particles. They are presented in the following table (see Table 5.1 and also axes in Figure 5.2).

Type of geometry	Size of applicable particles	x-dimension	y-dimension	z-dimension
1	0.009525 0.006755 0.003675	0.05	0.05	0.4
2	0.003175 0.003675 0.002675	0.04	0.04	0.125
3	0.0015 0.000925 0.000675 0.000325 0.00012	0.04	0.04	0.05

Table 5.1: The three different geometries.

Firstly, a cartesian grid was applied to the domain. Thereafter, it was thought that the centre volume of the modelled tank was of most interest and should be where the grid is the finest. For this reason, a logarithmic mesh was applied, concentrating the smallest cells in the area of interest. An example is shown in Figure 5.3.

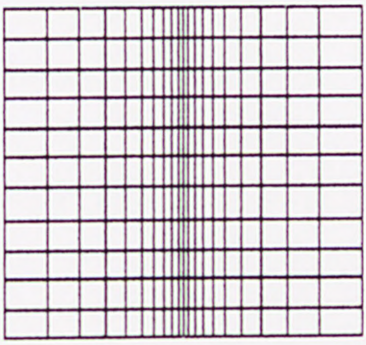


Figure 5.3: The logarithmic mesh of the inlet and outlet of the modelled tank.

From one type of geometry to another, the size of cells was different. The following table summarises the number of cells per side, the size of cells (for y and z directions) and the ratio for each type of geometries (see Table 5.2). The number which can be read under the name 'ratio' is the value of the ratio between the biggest size and the smallest size on the x-axis (which is the only axis on which the logarithmic mesh was applied).

Type of geometry	Number of cells	Ratio	Size of cells
1	20	3	0.0048
2	20	3	0.0016
3	20	4	0.0006

Table 5.2: A different mesh for each geometry.

5.2.1.2 Initial conditions

Once the geometry had been satisfactorily created, all the initial conditions of the problem could be specified. When these conditions were complete, then the 'command file' could be written (see section 5.2.3). The understanding of the problem (acquired in

Chapter.4) allowed to set up the initial conditions. These initial conditions defined the boundary conditions and ruled the way the problem was to be solved.

The general assumptions for the model were:

- 3-dimensional;
- isothermal;
- incompressible;
- standard fluid is water (this is the continuous phase);
- buoyancy for the solid particle (not for the fluid);
- the fluid is static;
- the initial speed of the particle is equal to 0;
- the initial position of the particle is the centre of the inlet, and;
- the only exchange between the particle and the fluid is of momentum (i.e. no exchange of mass or heat).

The set of initial conditions influenced the technique used for the solving of the equations. The requirements for the present model were to:

- use the Particle Transport Model (PTM) to model the settlement of the solid particle;
- model the solid particle until it reaches its terminal speed;
- get the values for the C_D, the R_{ep} and the speed of the solid particle returned in a separate file so the values can be checked with a calculator and compared with the ones given by the output file;
- reach an acceptable convergence, and;
- be able to change the formula for the C_D.

After the geometry has been created and the initial conditions have been specified, then the equations solved by the solver of the modelling package have to be thoroughly described in order to understand the power and limitations of the model.

5.2.2 The solving of the flow with particles

In order to model the settlement of particles using the commercial package, the Particle Transport Model (PTM) was used. This model was available in the CFD package and could be applied to the settlement of a single solid particle. It can also solve problems involving bubbles and drops. It is based on Newton's second law. The equations governing the fluid flow solved for the present exercise come from the basic laws of fluid dynamics:

- the mass conservation;
- the energy conservation, and;
- Newton's second law.

These laws form the commonly used Navier-Stokes equations. A brief presentation of the principles behind these basic laws is given below.

- Mass conservation:

The general principle behind the mass conservation is:

Rate of increase of mass in fluid element	=	Net rate of flow of mass into fluid element

- Newton's second law:

Again, the general principle is:

Rate of increase of momentum of fluid particle	=	Sum of forces on fluid particle

- Energy equation:

The general idea of energy conservation ca be presented as:

Rate of increase of energy of fluid particle	=	Net rate of heat added to fluid particle	+	Net rate of work done on fluid particle

In the present case, the flow was assumed to be isothermal, so there was no temperature gradient. On addition, there was no exchange of heat between the fluid and the particle. Therefore, the main equation solved for the particle can be presented as below (Naik 1996):

$$m_p \frac{dV_{pi}}{dt} = \frac{1}{2} C_D \rho A_p (V_{fi} - V_{pi}) \left| \overline{V}_f - \overline{V}_p \right| + m_p g_i$$

where i=1,2 representing the two cartesian c-ordinate directions x and y. The assumptions employed in this equation are that the particles are spherical, non-interacting and that there are negligible additional forces except for those due to drag and gravity.

The advantage of using a CFD commercial package for solving these equations is to be able to solve the presented equation with an iterative process (as opposed to use simplifications and approximations). The required elements to solve these equations were given in the set of initial conditions (i.e. the command file). The drag coefficient was either the default one from the package or the one introduced via a Fortran subroutine. As stated in Chapter.4, there are numerous formulae to calculate the drag coefficient. The default correlation within the CFD package is given by:

$$C_D = \frac{24}{R_{ep}} \left(1 + 0.15 R_{ep}^{0.687}\right)$$

(Schiller and Nauman 1932)

In the PTM, the particles are assumed to be perfectly spherical. As far as the settlement of a particle is concerned, there are two ways to introduce a shape other than spherical in the used package. The first way is to change the drag correlation to one adapted to the specific shape. The second way is to give two characteristic lengths of the particle in the command file. The first way was the selected option for the present model. The description of the initial conditions for the continuous and disperse phases are shown in the command file.

5.2.3 The command file

The command file is the file associated to the geometry file to solve the problem using the CFD package. This file contains the initial conditions concerning the fluid flow and the solid particles. It also contains the boundary conditions and general specifications for the flow and the way to solve the problem. It is written in 'command language' with keywords in a specific order. The command file was the same for every the four tests (the calibration test and the three other tests), except for two details:

- for the 'calibration test', the default C_D was used whereas other correlations were introduced for later tests, and;
- the initial position (at the centre of the inlet) of the solid particle had to correspond to the adequate geometry (the simple statement : 'Initial position = centre of inlet' was not possible in the command file).

The command file is presented below (see Figure 5.4) with the meaning of each group of keywords.

```
>>CFX4
  >>SET LIMITS
    TOTAL CHARACTER WORK SPACE 150000                 allocate memory for the job
  >>OPTIONS
    THREE DIMENSIONS
    BODY FITTED GRID
    CARTESIAN COORDINATES
    LAMINAR FLOW
    ISOTHERMAL FLOW                                   general conditions of the flow
    INCOMPRESSIBLE FLOW
    STEADY STATE
    USE DATABASE
    PARTICLE TRANSPORT
    PARTICLE BUOYANCY
  >>USER FORTRAN                                      the drag coefficient subroutine can be used
    USRDRG                                            (these two lines were not present for the calibration test)
>>MODEL DATA
  >>MATERIALS DATABASE
  >>SOURCE OF DATA
    PCP                                               use of the database for water properties
  >>FLUID DATA
    FLUID 'WATER'
    MATERIAL TEMPERATURE 2.8800E+02                   general conditions for fluid properties
    MATERIAL PHASE 'LIQUID'
  >>PARTICLE TRANSPORT MODEL
  >>MODEL CHARACTERISTICS
    NUMBER OF PARTICLES 1
    NUMBER OF ITERATIONS 1                            general conditions for the PTM
    PARTICLES
  >>PARTICLE PROPERTIES
    BASE PARTICLE DENSITY 2.39E+03
    BASE MATERIAL PHASE 'SOLID'                       general conditions for the particle properties
    BASE MATERIAL TEMPERATURE 2.8800E+02
  >>PHYSICAL PROPERTIES
  >>STANDARD FLUID
    FLUID 'WATER'
    STANDARD FLUID REFERENCE TEMPERATURE 2.8800E+02
  >>BUOYANCY PARAMETERS
    GRAVITY VECTOR 0.0 0.0 9.81                       buoyancy vector adapted to
                                                      the defined geometry
>>SOLVER DATA
  >>PROGRAM CONTROL
    MAXIMUM NUMBER OF ITERATIONS 100
    MASS SOURCE TOLERANCE 1.0000E-10                  general conditions for the solver
  >>UNDER RELAXATION FACTORS
    U VELOCITY 3.0000E-01                             under relaxation factors to improve
    V VELOCITY 3.0000E-01                             the convergence
    W VELOCITY 3.0000E-01
>>MODEL BOUNDARY CONDITIONS
  >>INLET BOUNDARIES
    PATCH NAME 'INLET'                                initial condition for the fluid
    NORMAL VELOCITY 1.0000E-06
  >>PARTICLE TRANSPORT BOUNDARY CONDITIONS
    POSITIONS IN X DIRECTION 2.5000E-02
    POSITIONS IN Y DIRECTION 2.5000E-02               initial position of the particle
    POSITIONS IN Z DIRECTION 0.0000E+00
    INITIAL PARTICLE DIAMETERS 6.7500E-03
    PARTICLE MASS FLOW RATES 1.0000E-04
    U VELOCITY 0.0
    V VELOCITY 0.0                                    initial velocity of the particle
    W VELOCITY 0.00001
>>STOP
```

Figure 5.4: The command file used for the CFD tests.

5.2.4 The USRDRG subroutine

One of the particularities of the used CFD package is that it contains a large selection of Fortran subroutines. These subroutines can easily be added to the command file to specify more scalars, boundary conditions, output data or to change default specifications. There are very simple to use:

- a specific keyword representing the subroutine needs to be added to the command file;
- the subroutine needs to be prepared for use in the appropriate way (each subroutine contains an example to guide the user), and;
- when the user runs the solver, the subroutine file needs to be specified.

The used Fortran subroutine was the one called USRDRG, which overwrites the default drag coefficient. For every test, apart from the calibration one, the command file was used along with the Fortran subroutine file. In the subroutine file, a selected equation for the drag coefficient was written in Fortran. In the present case, the values for R_{ep}, C_D and the settling speed were also asked to be returned to an independent file for verification. This file is presented and commented below (see Figure 5.5):

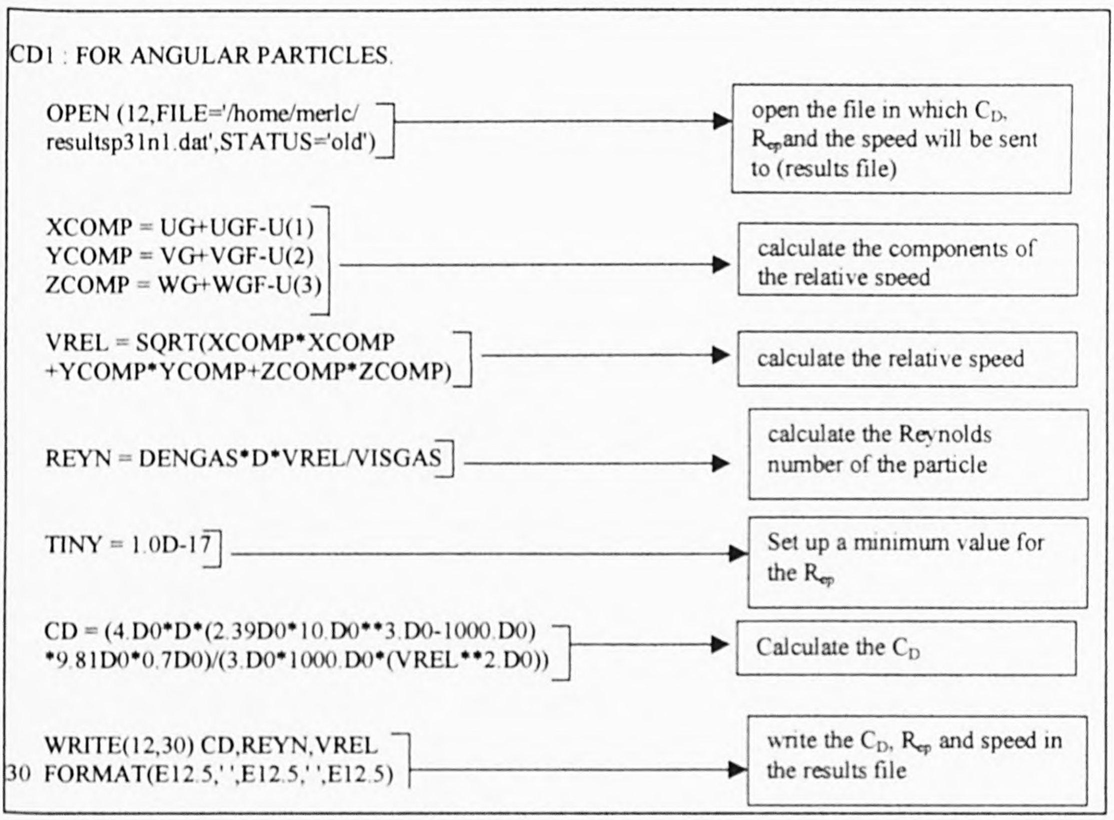


Figure 5.5: The USRDRG subroutine.

Figure 5.5 represents an example of the USRDRG subroutine used for the present study. The other subroutines are shown in Appendix.6.

5.2.5 The 'calibration' tests

5.2.5.1 Test using the default C_D

This was called the calibration test as the default drag coefficient of the CFD package was used to model the settling of the particle. For this first test, the presented command file (see section 5.2.3) was used without the subroutine USRDRG. The model was first run with the specifications of the particles used for the calibration exercise (see section 3.5.3). The particles were spheres made of Teflon with the following characteristics:

Particle	Sphericity	Diameter	Density	v_{exp}	R_{ep}
No	**n/a**	**m**	**kg/m3**	**m/s**	**n/a**
1	1	0.009525	2312	0.548	4554
2	1	0.003175	2316	0.333	839

Table 5.3: Characteristics of the particles used for the first 'calibration' test.

A comparison was then made between v_{cfd}, v_{exp} and v_{th} (CFD, experimental and theoretical values respectively). The agreement between all these values was very good (see table 5.4).

Particle	v_{exp}	v_{th}	v_{cfd}
No	**m/s**	**m/s**	**m/s**
1	0.548	0.586	0.587
2	0.333	0.345	0.342

Table 5.4: Comparison between experimental, theoretical and CFD values for the first 'calibration tests'.

These results can be found in Appendix.7 along with all the results from the computational tests. After this first 'calibration' test was successfully carried out, the second 'calibration' test with different types of particles could be conducted.

The following tests were conducted using the same command file as before (still with the default C_D). They aimed at comparing CFD settling speed values (using its standard C_D) with v_{th} and v_{exp}. This comparison was expected to validate the experimental values but also to show a need to adapt the drag coefficient formula for the shape of particles. All the results from this test can be seen in Appendix.7. A graph (see Figure 5.6) showing the different points is presented below:

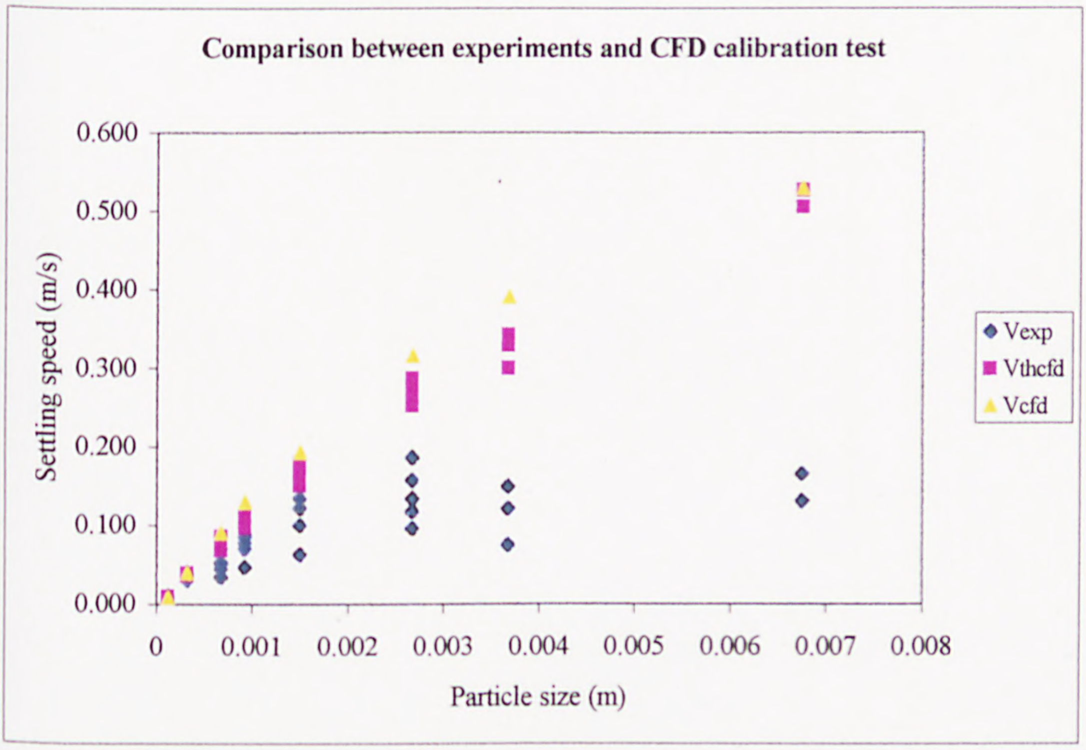


Figure 5.6: Comparison between experiments and CFD calibration test.

As it can be noticed on Figure 5.6, there is a very good agreement between v_{th} and v_{cfd}; whereas v_{cfd} values are far from v_{exp}. Morever, the bigger the particles, the larger the divergence. This can obviously be explained by the fact that the default equation for the C_D does not take into account the shape of the particles. The system assumes that all the particles are spherical. That is also why, for each size, the CFD package only gave one value for the settling speed. It did not differentiate the particles by their shape, as it is not a parameter which is taken into account in the simulation. Another observation is the fact that v_{cfd} values are always above v_{exp} values. The reason for this phenomenon is that the tests done with the CFD package were in fact done with the equivalent spheres in terms of diameter. The CFD package was always modelling the settlement of particles which had the same diameter as the real particles. And therefore, those particles had a volume (and then mass) much bigger than the real ones. That is why the settling speeds given by the CFD package are always above the experimental ones. This phenomenon was called the 'equivalent sphere phenomenon' in order to simplify the comments on the following tests.

As a last comment from this graph, it can also be said that there is an obvious relationship between v_{cfd}, v_{th} and v_{exp}:

$$v_{cfx} \geq v_{th} \geq v_{exp}$$

5.2.5.2 Summary of the 'calibration' tests

These first two 'calibration' tests showed good agreement between the v_{cfd} and v_{th} values. For the first 'calibration' test, v_{cfd} values were also very close to v_{exp}. However, this good agreement was certainly not observed for the second 'calibration' test. The results of the 'calibration' tests are summarised in Appendix.7. Errors were calculated between v_{exp}, v_{cfd} and v_{th} using the previously presented equation:

$$E = \frac{\Sigma(y_{fit} - y_{exp})^2}{\Sigma y_{exp}^2} * 100$$

The error for the simulation of the experimental values was very large with an average of 220%. The average error for the simulation of the theoretical values was much lower: 2%. Therefore, there was a need to adapt the drag coefficient more to the shape of particles. This was why different drag coefficients, which were presented in section 4.3.1 were used in the next tests.

5.3 TESTS FOR DIFFERENT SIZES AND SHAPES

5.3.1 Results using C_{D1}

This test was conducted using the selected C_{D1} for each particle (see Table 4.2). Here, the same command file as the previous tests was used, but this time, the subroutine USRDRG was used. Test No1 was longer to implement than the 'calibration' ones as two different subroutines were used (one for each correlation selected under C_{D1}). Moreover, as for every tests presented in this chapter, the geometry was different for each range of sizes (see section 5.2.1.1). The final results of test No1 are presented in the following graph:

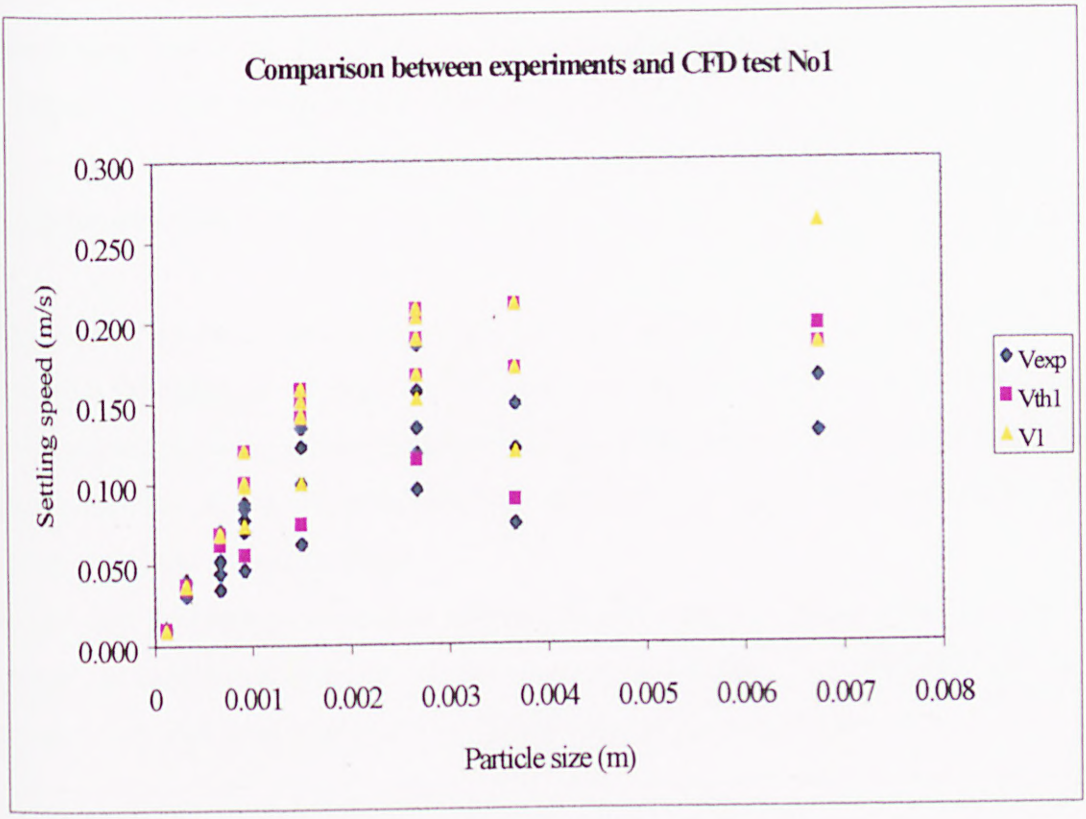


Figure 5.7: Comparison between v_1, v_{th1} and v_{exp}.

On this graph, v_{th1} and v_1 correspond respectively to the theoretical speed and the modelled speed from Test No1. It can be observed that all the values were much closer to each other than in the second calibration test. For this test, the CFD package gave different points for each size as the drag coefficient was more adapted to the shape of the particles (C_{D1} actually takes into account the sphericity). It can also be noted that for this test, the same relationship between v_1, v_{th1} and v_{exp} was found:

$$v_1 \geq v_{th1} \geq v_{exp}$$

For Test No1, the error was calculated using the same equation as for the 'calibration' tests. The average values for error were:

- on experimental values: 14.9%
- on theoretical values: 1.57%.

Therefore, the results from Test No1 are in better agreement than that of the calibration tests. They are closer to the experimental values but also to the theoratical ones. This shows again that there was definitely a need to adapt the drag coefficient to the shape of the particle. These results are also shown in Appendix.7.

5.3.2 Results with C_{D2}

This test, Test No2, was conducted in exactly the same way as Test No1 but with different formulae for the drag coefficient. In this test, four different correlations for C_D were introduced using the subroutine USRDRG. Here, none of the C_D takes into account the sphericity of the particles directly. All the C_Ds used were correlations which corresponded to a specific shape.

Again, the geometries were also adapted to each range of sizes. This test was even longer to implement because of the number of changes (in USRDRG and in the geometries). The final results of Test No2 are shown in the graph below:

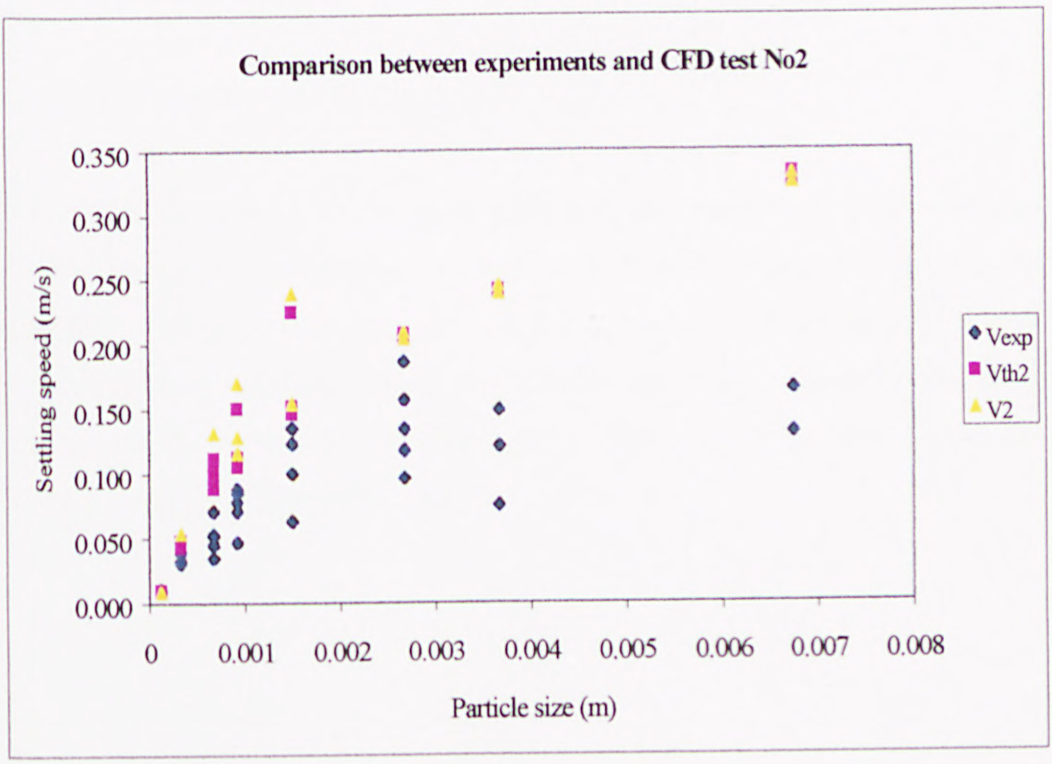


Figure 5.8: Comparison between v_2, v_{th2} and v_{exp}.

As in Test No1, v_2 and v_{th2} are respectively the speed given by the CFD package for Test No2 and the theoretical speed calculated for Test No2. The same relationship as previously was found:

$$v_2 \geq v_{th2} \geq v_{exp}$$

It can also be observed on the graph that the agreement between all the types of values is not as good as in Test No2. It was expected that, because of the greater number of drag coefficients used for this test, the results would be closer. But in fact, they were not. The average errors proved this observation:

- on experimental values: 77.46%
- on theoretical values: 0.78%.

Therefore, the main conclusion was that, it would be more effective to have one formula which would take into account the shape of the particle rather than to use several different correlations for each type of shape. Moreover, the selected correlations were given for regular shape whereas the present particles had very irregularly shapes.

5.3.3 Results with the new C_D

For Test No3, the new C_D developed by the author (see section 4.4) was introduced. The test was simple and fast to implement as only one USRDRG subroutine was needed. The results from Test No3 were expected to be very close to the experimental values as the new C_D had been developed using the experimental values. Nevertheless, it was an important test to see how the CFD package would 'react' to the new correlation. The following graph shows the final results.

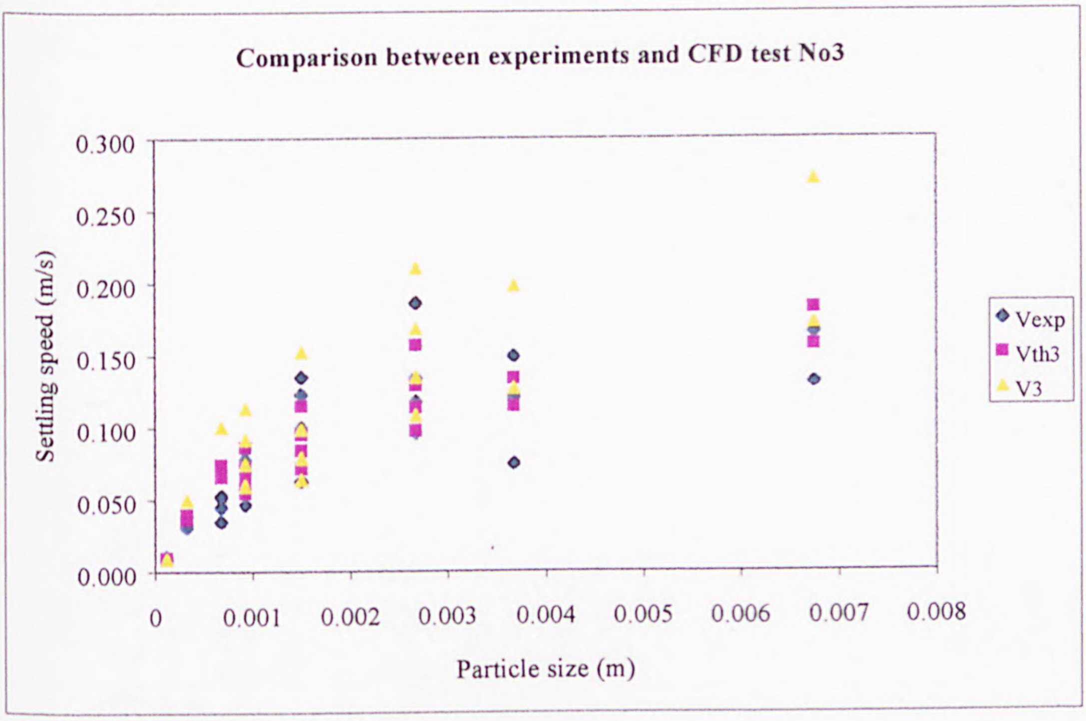


Figure 5.9: Comparison between v_3, v_{th3} and v_{exp}.

From the graph, it was clear that these results were in good agreement with the experimental values. As stated before, this was obviously because the C_D used was developed from the experimental values. Moreover, it was also the easiest to implement as it adapted to every type of particles. The average error was as follows:

- on experimental values: 19.07%
- on theoretical values: 12.09%.

For Test No3, there was no obvious superiority order, so the usual relationship was not observed. It can be noticed that the average errors were slightly higher than with C_{D1}. However, the new drag correlation is a single equation which can be applied to cuttings of any shape.

5.4 COMPARISON WITH OTHER WORKS

5.4.1 Comparison with experimental works

For this comparison, the same experimental data as in section 4.3.2 were used. They came from Fang 1992, Mamak 1964 and Gibbs *et al* 1971. They were compared with the CFD results from Test No1, No2 and No3. The following graph summarises the final results.

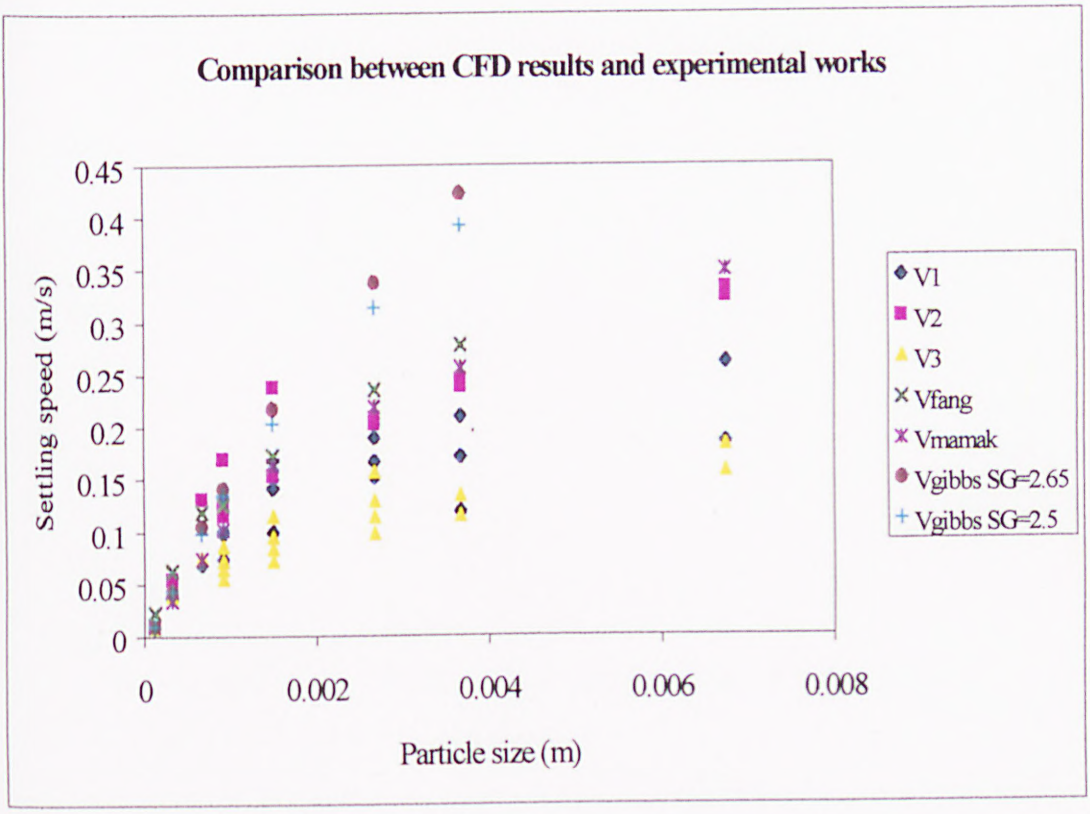


Figure 5.10: Comparison between CFD results and experimental works.

A first observation from this graph is that v_3 values are closer to v_1 than they are to v_2. Again, this is because the sphericity was directly taken into account in Test No1 and No3, but not in No2. Another observation is that all the experimental values are higher than the modelled ones. This is because the majority of the particles used for these experimental tests were spherical. Therefore, for the same size and density, they will fall quicker. Moreover, in most cases, the density for the experimental particles (2.65 or 2.5) was larger than for the modelled ones (2.39). The best comparison with experimental work would be using particles with a known sphericity and the same density for all.

5.4.2 Comparison with correlations

This test was conducted using the correlations presented in section 4.3.3. These were developed by Rubey 1933, Chien 1972 and Moore 1986. The same tests (No1, No2 and

No3) as in the previous section were compared with the correlations data. The final results are summarised in the following graph:

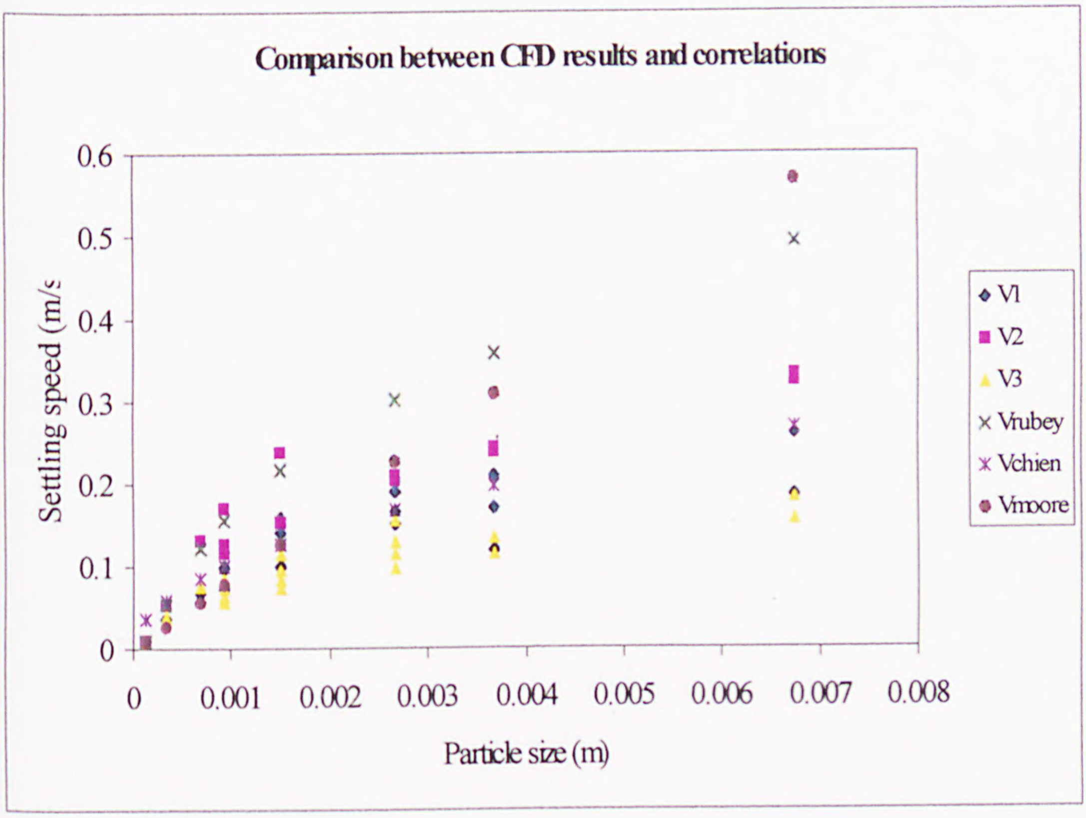


Figure 5.11: Comparison between CFD results and correlations.

Here, a good agreement can be observed apart from for the particles with a size equal to 0.00675 (the biggest particles). Of course the comments about the relationship between v_1, v_2 and v_3 made in the previous section are still valid. The best agreement is found with Chien's correlation results. This can be explained by the fact that his correlation was developed from work done on real drill-cuttings. The worst agreement was with Rubey's correlation. This was expected as Rubey's correlation is for round particles. It also has to be noted that the change of regimes (laminar, transition or turbulent) is a factor in the agreement between CFD results and correlations values. Some correlations are better for certain regimes and therefore might agree better with the CFD results.

5.5 SUMMARY

As a conclusion, it can be said that excellent agreement was found between the computational results and the theoretical results. Results between computational and experiments were closer when using a C_D taking into account sphericity. Test No3 using the new C_D showed a good match between computational and experimental data. Moreover, computational results were relatively close to the correlations data apart from for big particles.

In Chapter.4, the experimental data had been compared to other experimental works and correlations. In Chapter.5, it was compared to computational data for further analysis. The results showed that, when using a commercial package, the default equations are not always the best adapted to the studied case. When the structure of the package is flexible, more specific correlations can be introduced. However, the package was a useful tool to support the modelling of the particles settlement.

Chapter.6
THE NEW DATABASE

6.1 INTRODUCTION

In Chapter.1 and Chapter.2, environmental concerns and cuttings dispersion models were presented. The required input data for these models is always the same: oceanographic conditions and the characteristics of the drilling wastes. Unfortunately, there is a lack of knowledge of the drilling waste characteristics (Carles *et al*, 1999). Once, this new data is created, it has to be put in a format relevant and adequate for the users. If used for prediction purposes (i.e. prediction of the dispersion or hole-cleaning processes), the new data had to be correlated to data that engineers would know in advance. Prior to drilling a well or a section of a well, a drilling program is written, containing all the expected drilling conditions. Therefore, by using correlations between the drill-cuttings characteristics and drilling parameters, users would be able to predict the cuttings characteristics.

6.1.1 Introduction to the database

As it stated earlier in this thesis, there is an urgent need to know more about the drill-cuttings characteristics. These characteristics are influenced by the drilling conditions and it is necessary for the present work to determine correlations between these two sets of parameters. In order to determine the drill-cuttings characteristics, laboratory experiments were carried out as described in chapter.3. Through an offshore survey, corresponding drilling parameters were obtained. Correlations between the particle characteristics and the drilling conditions were found using multiple regression models. Due to the number of samples and data, and also to help in the process of finding the adequate equations, a statistical package called Minitab was used.

The obtained equations were then introduced in a FORTRAN 90 program to predict the size distribution curves when the drilling program is known. The development of the

database is described in detail in this chapter. Firtsly, the general statistics used are presented and the procedures to obtain the new correlations are explained.
Such a database should be a reliable tool for simulation models. Computing packages modelling dispersion of drilling wastes or drilling efficiency should benefit enormously from the use of this database. The main structure of the database is in FORTRAN 90, which means that the database could easily be introduced in any model such as Newcut (Carles and Bryden 1999) and PROTEUS (BMT 1999). Otherwise, the new equations (i.e. the correlations) can simply be added to any system. The new correlation for the drag coefficient presented in Chapter.4 was also introduced in the database. This is to advise the user on aquatic settlement properties of the drill-cuttings.

6.1.2 Objectives of the database

The objectives for the development of such a database were several and varied. In summary, these were to:

- increase the knowledge on the correlations between the drill-cuttings characteristics and the drilling parameters;
- provide a simple and easy-to-use tool for predicting the drill-cuttings characteristics when the drilling conditions are known,
- avoid using guesstimates for EIA (Environmental Impact Assessment) or other studies (like hole-cleaning predictions or even the study for cuttings disposal alternatives);
- advise the user on the aquatic settlement properties of drill-cuttings, and;
- enable the user to introduce the database in any relevant model.

Therefore, it is believed that this new database will be useful for predicting the type of cuttings obtained from a well for a specific project such as: environmental research, biological and chemical research and also cuttings removal alternatives. On another hand, more data, even from other parts of the world could simply be added to the database. New correlations would then have to be defined.

6.1.3 General statistics

6.1.3.1 Introduction

For this study, a high numbers of predictors, data and samples were present. Therefore, it was important to find a reliable and effective (in time and effort) way to correlate the drill-cuttings size with the drilling parameters. The final aim was to be able to correlate the points of the size distribution curves (see the 'cumulative' curves in Appendix.2) with their corresponding drilling data. So, the predictors were the selected drilling parameters and the dependent variables representing the points from the cumulative curves (see y1 to y8 on Figure 6.1). Figure 6.1 shows this basic principle.

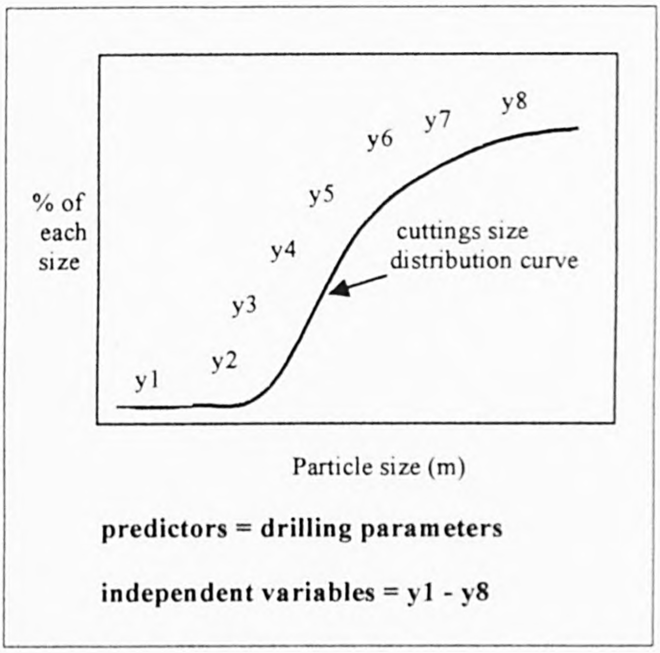


Figure 6.1: The predictors and independent variables.

First of all, some basic statistics need to be understood. As a common (and advised) mean to achieve the objectives of this study, the multiple regression analysis was used. Regression analysis is concerned with measuring the way in which one variable is related to another. It illustrates how changes in one variable help to explain changes in another variable. It is a statistical procedure that can be used to develop a mathematical equation showing how variables are related. The equation can then be used for estimation or prediction purposes (Wilson 1999).

There are two types of variables: the independent ones and the dependent ones.

If y is predicted from a knowledge of x, then y is the dependent variable (i.e. the points from the curves called y_1 to y_9) while x is the independent one or predictor (the drilling parameters). Firstly, it is useful to observe how closely the variables are related to each other. Here, the strength of the linear relationship needs to be assessed: this is the process of correlation.

6.1.3.2 The coefficient of correlation

The sample coefficient of correlation r measures the strength of the linear relationship that exists within a sample of n bivariate data. A very common formula used to calculate r is called the 'Pearson product-moment':

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

$$\bar{y} = \frac{\Sigma y}{n}$$

$$\bar{x} = \frac{\Sigma x}{n}$$

n is the number of observations, samples.

(Pindyck *et al* 1981)

It has to be noted that $-1 \leq r \leq 1$:

- when $r = +1$, there is a perfect positive linear relationship;
- when $r = 0$, there is no linear relationship, and;
- when $r = -1$, there is a perfect negative linear relationship.

(Wilson 1999)

For example, a high and positive correlation ($r > 0.7$) indicates that a straight line relationship exists bewteen y and x with a positive slope.

This method is the one used for the purpose of this study. A realistic example is shown later in this chapter.

6.1.3.3 The least square method

Very commonly, the regression analysis implies the use of the Least Squares Method (LSM). This method, used to develop the estimated regression equation, minimises the sum of the squared residuals (the deviations between the observed values of the dependent variable y_i, and the modelled values of the dependent variable, $\hat{y}_i$). In the present case, it shows the deviation between the experimental values and the values found using the correlations. This method defines the 'best line' as the line such that the sum of squares of the errors (SSE) is a minimum (Draper 1966). The basic principles are as follows:

(deviation) Error = observed y-value - estimated y-value

Error $= y_i - \hat{y}_i$

Sum of squares due to error: SSE $= \Sigma(y_i - \hat{y}_i)^2$ is a minimum

The equation of the line developed using the least squares method is referred as the estimated regression equation. The line expresses the average relationship between the two variables (i.e. average y for a given x). It is called the linear regression of y on x.

For the present study, a linea system was considered. So, the estimated regression equation was:

$\hat{y} = a + bx$

$\hat{y}$ = estimated y-value

a = y-intercept of the line

b = slope (gradient) of the line

The procedures for finding a and b using the method of least squares is complicated as it involves differential calculus. It can be simplified to the following expressions for determining a and b:

$$b = \frac{n\Sigma xy - \Sigma x\Sigma y}{n\Sigma x^2 - (\Sigma x)^2}$$

$$a = \overline{y} - b\overline{x}$$

(Pindyck *et al* 1981)

This method is simple and very commonly used to 'fit' curves. It was actually tried to 'fit' the cumulative curves using the LSM created in Excel. This method was investigated using a linear and quadratic system (for the fitting curves). Unfortunately, the amount of data was too large and the fit too low to conclude with this method in Excel. This is why it was decided to use a commercial statistical package. This method was not suitable for these correlations. However, this was the method used to find the new drag coefficient (section 4.4.4). In this specific case, the columns needed were:

- one for the Reynolds numbers;
- one for the y-values (i.e. the experimental drag coefficients);
- one with the values from the 'fitting' equation (i.e. estimated y-values);
- one for the changing variables within the fitting equation (in the present case, it was 'a', 'b' and 'c' as defined in section 4.4.4), and;
- one for the errors as defined above.

As stated previously, the values for 'a', 'b' and 'c' needed to be changed until the sum of the errors reaches a minimum value. When the minimum value is judged acceptable, then the correlation is found. This method was very successful for the new drag correlation. For the present correlations, a statistical package called Minitab was used. More statistics need to be presented in order to understand the work done with the package.

6.1.3.4 Quality of fit

Once a model is found, it is needed to assesss how well the model fits the original data. Therefore the differences between the actual values of the dependent variable y_i and the corresponding fitted value $\hat{y}_i$ need to be calculated. These values $y_i - \hat{y}_i$ are called residuals. The coefficient of determination r^2 provides a measure of goodness of the fit of the estimated regression equation of the data.

Coefficient of determination r^2 = (Correlation coefficient r)^2

This is particularly useful in describing the closeness of the relationship between x and y. In the estimated regression of y on x, it is tried to explain the total variation in the observations of y by the variations in x. Rarely is all the variation in y explained by the variation in x alone. There is usually an explained proportion and an unexplained proportion. In the present case, it means that not only one drilling parameter can explain the changes in the position of the points on the curves. It is a group of drilling parameters which can explain an acceptable amount of the variation in the dependent variable.

The coefficient of determination is the proportion of variability of the dependent variable y, accounted for, or explained by, the independent variable x.

$$r^2 = \frac{\text{sum of the squares explained by regression}}{\text{total sum of squares (before regression)}} = \frac{SSR}{SST} = \frac{\Sigma(\hat{y} - \bar{y})^2}{\Sigma(y - \bar{y})^2}$$

$(y_i - \hat{y}_i)$ represents the error in using $\hat{y}_i$ to estimate y_i. It is referred as the ith residual.

Sum of squares due to regression: $SSR = \Sigma(\hat{y}_i - \bar{y})^2$

Sum of squares due to error: $SSE = \Sigma(y_i - \hat{y}_i)^2$

Total sum of squares: $SST = \Sigma(y_i - \bar{y})^2$

With, SST = SSR + SSE.

It has to be noted that: $0 \leq r^2 \leq 1$. The better the fit, the higher r^2. Therefore, the aim of the exercise was to get an r^2 above 0.8 if possible.

6.1.3.5 Aims of the analysis

When a number of explanatory variables are available for selection in a multiple regression model, the criteria for selecting a resultant equation usually involves:

- making the equation as useful as possible for predictive purposes so that reliable fitted values can be obtained, and;
- including as few explanatory variables as possible in order to reduce the costs in using the model.

Therefore, in the present case, a simple linear equation (i.e. $y = a + bx_1 + cx_2 + dx_3$) was chosen. It was a simple equation to implement and it was thought that it could achieve the purpose of the exercise. Moreover the number of explanatory variables (i.e. the drilling parameters) was kept as low as possible. The aim was to find a reasonable number of predictors which gave an acceptable fit.

The terms in the model were assessed for their extra contribution to the model by their p-value ($p > 0.05$) for inclusion. In other words, the assessment was done on the extra variation explained in the dependent variable when all the other variables were already present in the model. So, for example, when Pearson coefficients between all the independent and y_1 were calculated, they only indicated the influence of each individual independent on y_1. When the multiple regression model was applied, it measured the influence of all the independent together on the dependent y_1. This p-value was useful to observe the drilling parameters with a significant influence on the variations of the dependent variable.

Another aim of the analysis was to verify if the obtained models were statistically correct. Therefore, as well as obtaining good results for values like p and R^2, the residuals values were also checked. The residuals were expected to be independent and normally distributed (bell-shaped) with constant variance and zero mean (Wilson 1999). An example of this specific validation analysis is presented in the next section (section 6.1.4).

6.1.4 Useful information about Minitab

6.1.4.1 Introduction

In the previous section, some basics statistical theory was presented. All of these principles are used in Minitab. Minitab is a powerful statistical software program that provides a wide range of basic and advanced data analysis capabilities (Ryan, *et al* 1994). Minitab can automatically operate the common multiple regression model. It gives useful printouts with all the information needed to judge the quality of the model (e.g. values for p and R^2). It calculates correlations and values of different coefficients using the theory described in the previous section.

6.1.4.2 Minitab outputs

Minitab printouts automatically give the coefficient of determination but expressed as a percentage. It has to be noted that maximising R^2 is equivalent to minimising SSE. Therefore, in the regression model, the highest possible value for R^2 is sought. In Minitab, this is expressed as a percentage: $R^2 = 100\ r^2$. In the case of this present study, it was thought that 80-85% was a good value for R^2. It is a high enough value to be trusted but still achievable with the possessed data.

Another important mean to assess the value of the obtained model with Minitab is to check the independency and normality of the residuals. This is a very good way to check the stability of the model. It shows that the good fit of the correlations is not just a 'coincidence'. In order to do so, four different plots are obtained for the residuals of a single model applied on a single sample (see Figure 6.2):

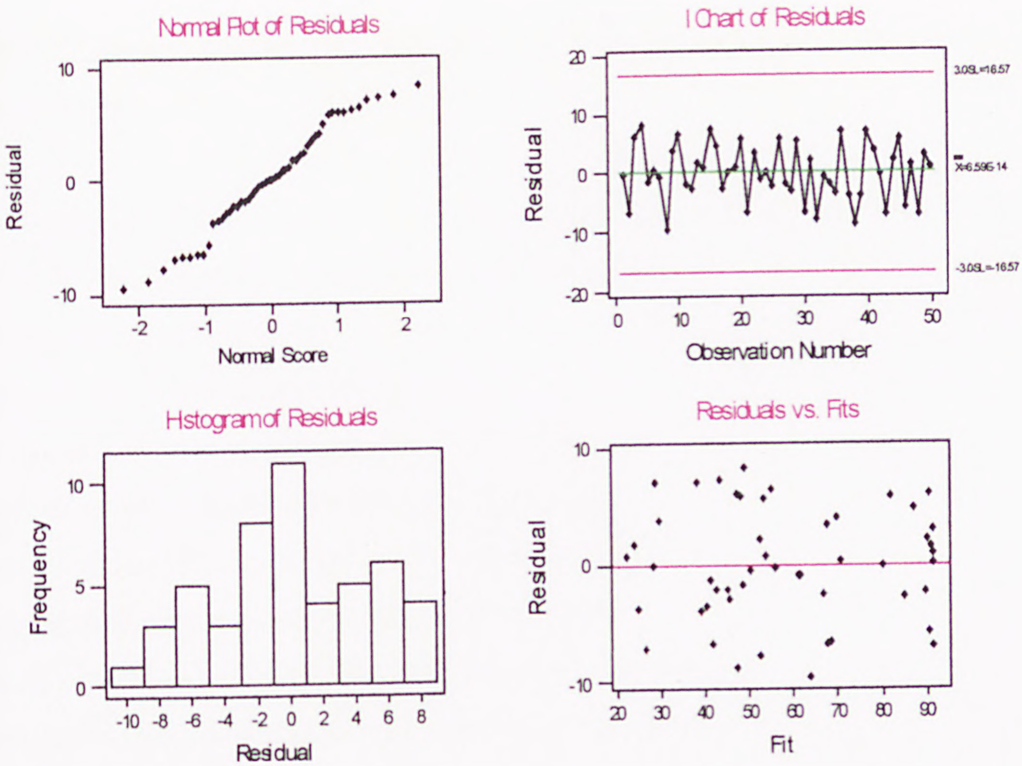


Figure 6.2:An example of residuals plots.

As stated previously, the residuals are expected to be independent and normally distributed (bell-shaped) with constant variance and zero mean. In the plot given by Minitab, the top left curve should be an approximate straight line for normality. The bottom left histogram should represent a bell-shaped curve for normality (although it only tends to be for large data sets). The top right scatter plotting should be a random sequence for independence (i.e. no long runs above or below 0 and no regular oscillations). Finally, the bottom right set of points should show a random 'shotgun' display for no outliers and constant variance (i.e. no high or isolated values and no wedge shape) (Wilson 1999).

6.1.4.3 Minitab 'special' tests

Minitab also runs 'tests for special causes'. They are 8 tests dealing with the distribution of residuals (top right scatter plotting on Figure 6.2). Three different zones are determined prior to run the tests (see Figure 6.2):

- zone A: the area up to one standard deviation from the center line;
- zone B: the area between one and two standard deviations from the center line, and;

- zone C: the are between two and three standard deviations from the centre line (Ryan 1994).

If the sample failed one or more of the tests, numbers appear on the scatter plotting (see Figure 6.2). These numbers correspond to the following tests:

1- one point beyond zone A;

2- nine points in a row in zone C or beyond;

3- six points in a row, all increasing or all decreasing;

4- fourteen points in a row, alternating up and down;

5- two out of three points in a row in zone A or beyond;

6- four out of five points in a row in zone B or beyond;

7- fifteen points in a row in zones C, above or below center, and;

8- eight points in a row beyond zones C, above or below center.

The presented outputs are a useful tool to check if the residuals meet the requirements. It is a guarantee of the quality of the model. For example, a model could have an acceptable value for R^2, but residuals not fulfilling the requirements. In this case, the model would have to be changed until a balance is found between the R^2-value and the residuals tests.

6.2 THE STRUCTURE OF THE DATABASE

6.2.1 Classification and format of the input data

In order to create the database, the input was analysed and classified. As seen in Chapter.3, a wide range of drilling parameters were available for each sample. However, only a limited number of those parameters will have a significance influence in the prediction of the 'ys'. Therefore, the drilling parameters had first to be selected, then classified and finally formatted in order to be introduced into the database. The choice and classification were based on advice from geologists and drilling engineers, but also books (Press *et al* 1994, Kennedy 1983, Devereux 1998, UKOOA 1997 and Glennie 1997), notes (Glennie, 1999) and catalogues (Reed Tool 1997 and Hycalog 1994).

Some of the input data was in the form of word (e.g. stratigraphy), so dummy variables had to be used to implement the presence or absence of that variable in the system. Dummy variables (their value was either equal to one or zero) were used for: 'mud', 'drilling-bit', 'stratigraphy' and 'ROP'. Dummy variables can also be called indicator variable. The classification of the independent variables is presented in the table below (see Table 6.1). Each independent variable was either represented by a dummy variable or by a number (variables in bold in Table 6.1).

Drilling parameters	**Independent variables**
Section	**23.5 12.25 17.5 8.5**
Depth	**any number**
Mud	WBM SBM
Drilling-bits	Tooth Insert PDC
Stratigraphy	Pliocene Miocene Oligocene Eocene Paleocene Cretaceous Jurassic Triassic Quaternary
ROP (Rate of penetration)	0/20 20/40 40/60 60/100 >100

Table 6.1: Classification of the drilling parameters as independent variables.

Every drilling parameter for each sample was classified and 'normalised' using the dummy variables when necessary. Therefore, at that stage, each sample had a combination of six normalised drilling parameters (represented by many more dummy variables) and nine values for the size distribution (e.g. the dependent variables: y1, y2, y3, y4, y5, y6, y7, y8 and y9). So, the final aim was to find one correlation which could predict y1 for example using the drilling parameters. A total of eight correlations was needed. Because of the type of cumulative curve chosen, y_9 (the last point of the curve) was always equal to 100, so it did not need to be modelled.

The use of dummy variables was in fact a mean to incorporate a term of 'failure' or 'presence' into the regression model. To make it clearer, an example from this study is presented below:

- if WBM was equal to '0', then WBM was not used for that specific sample; the independent variable was not 'present' in the model. Here, SBM is then equal to '1'.

It becomes more complicated when a independent variable such as 'Stratigraphy' has nine levels (rather than two levels for the mud). To handle this problem, it is needed to create a new two-level dummy variable for each different level (Anderson *et al* 1996). Therefore, Pliocene, Triassic, Miocene... etc were represented by a simple dummy variable (equal to '1' when present and equal to '0' when not present). Some of these dummy variables were found to be highly correlated with some others, and were therefore removed from the system. As well as the single independent variables, their cross-products were also considered. It is common practice to calculate all the cross-products and see their influence on the model. A single independent variable might not have a significant contribution to the model but its cross-product with another single independent variable might be an important predictor. Therefore, all the cross-products were calculated. Some of them had to be taken off the system as their values were constantly '0'. Some matrices are shown in the following example for case No1, No2 and No3 (each of them with a different bit and mud):

$$[\text{Bits}] = \begin{bmatrix} \text{No1} \\ \text{No2} \\ \text{No3} \end{bmatrix} = \begin{bmatrix} \text{Tooth} & \text{Insert} & \text{PDC} \\ \text{Tooth} & \text{Insert} & \text{PDC} \\ \text{Tooth} & \text{Insert} & \text{PDC} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[\text{Mud}] = \begin{bmatrix} \text{No1} \\ \text{No2} \\ \text{No3} \end{bmatrix} = \begin{bmatrix} \text{WBM} & \text{SBM} \\ \text{WBM} & \text{SBM} \\ \text{WBM} & \text{SBM} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$$

In case No1, a Tooth bit was used with WBM; in case No2, an Insert bit was used with SBM; and finally, in case No3, a PDC bit was used with WBM. These matrices are described to show that for example, 'bits' had 3 levels, each of them represented by a dummy variable. When 'Tooth' is present for example, the other levels are automatically absent (i.e. equal to 0). The following example shows the calculation of cross-product between two variables in the three cases presented above. The first two matrices show the same cases but only for 'Tooth' and 'WBM' (rather than 'bits' and 'mud').

$$\begin{bmatrix} No1 \\ No2 \\ No3 \end{bmatrix} = \begin{bmatrix} Tooth \\ Tooth \\ Tooth \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} No1 \\ No2 \\ No3 \end{bmatrix} = \begin{bmatrix} WBM \\ WBM \\ WBM \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

Then, the cross-product in this case would be:

$$\begin{bmatrix} No1 \\ No2 \\ No3 \end{bmatrix} = [Tooth] \times [WBM] = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Other predictors like the logarithm of 'section' and 'depth' were also included in the system to observe their influence on the models. They are represented in the system as normal numbers.

6.2.2 Available combinations

The input data was selected, classified and formatted. This section presents the available combinations within the database. For example, it shows the number of cases where 'Tooth' was present. It also gives some notes about 'constant' combinations. Table 6.2 summarises the number of cases with each variable present.

Stratigraphy	Olig	Eoc	Paleo	Cret	Jur	Quat
Cases	7	6	8	21	10	5

ROP	0/20	20/40	40/60	60/100	>100
Cases	39	13	2	1	2

Section	23.5	17.5	12.25	8.5
Cases	4	27	19	7

Bits	Tooth	Insert	PDC
Cases	22	14	21

Mud	WBM	SBM
Cases	53	4

Depth varied from 530.5 m to 4612 m.

Table 6.2: The available cases for the database.

In the table for 'stratigraphy', the variable were represented by the first letters of their real names (for convenience in the presentation). Amongst the 57 combinations available, some 'constant' combinations were noticed:

- Jurassic - PDC - 8.5 - WBM - 0/20;
- 23.5 - Tooth - >100 - WBM, and;
- SBM with either PDC or Insert.

These 'constant' combinations reflect some of the common practice in drilling engineering in the North Sea.

6.2.3 Normality tests

The previous sections concentrated on the drilling parameters as input data in the database. This section focuses on the dependent variables (the 'ys'). Using Minitab, some primary tests can be run to assess the 'state' of the data or even the expected complexity in finding a good model. One of these tests called the 'normality test' was run on the dependent variables (i.e. the y-values). The normality test generates a normal probablity plot and performs a hypothesis test to examine whether or not the observation follow a normal distribution (Minitab, 1997). The results were obtained using the descriptive statistics within Minitab.

For a sample to pass the test, it needs to have an A-squared lower than 0.5 (see Figure 6.3). In the case of the samples used for the present study, only three 'ys' 'passed' the test:
- y_1, y_2, y_3, y_4 and y_5 had higher value than 0.5 (from 4.822 to 0.929), and;
- y_6, y_7 and y_8 had value equal or lower than 0.5 (from 0.523 to 0.382).

This normality test can be presented under two forms:
- a histogram with a 'bell-shaped' general appearance, or;
- a curve which should be as close to a straight line as possible. Therefore, as it can be seen on the example (sample y_4 in Figure 6.3), the distribution does not represent a very straight line.

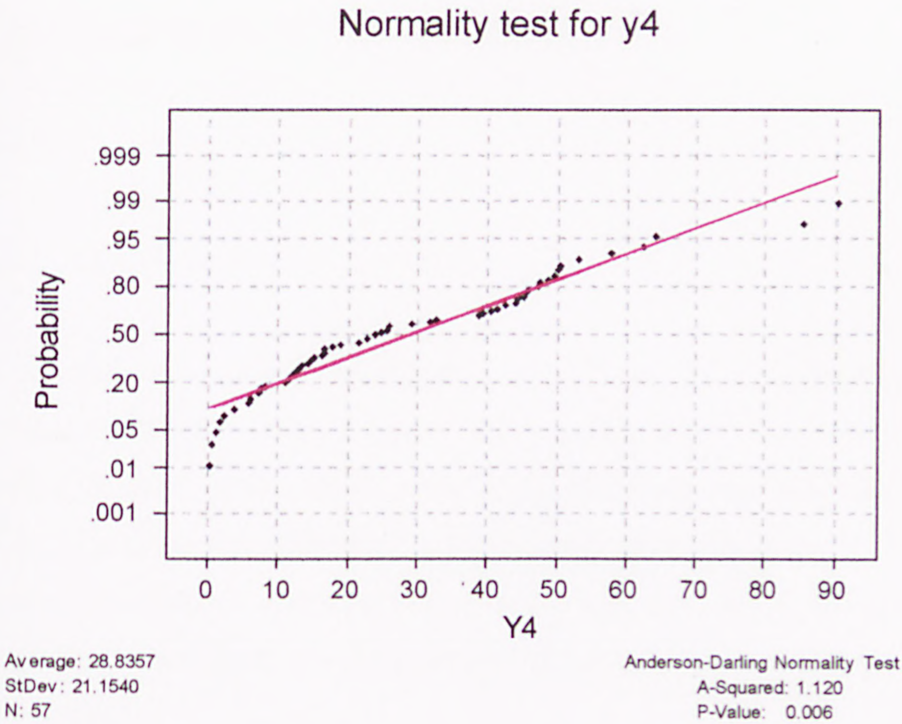


Figure 6.3: An example of the normality test.

In this case, it can be noticed that y_4 failed with an A-squared value of 1.12. The other numbers represented on the printout were not used for our study. The A-squared values were calculated over the 57 observations from the laboratory experiments. They give an evaluation of how 'sorted' (i.e. distributed) the data in the sample is. When the sample is normally distributed (i.e. with as straight a line as possible), one would expect to find a model more easily and also more accurate. That was absolutely verified in the next section of this chapter. The normality tests for each sample are presented in Appendix.7. It has to be noted that from y_1 to y_5, the data was badly distributed with high values for the A-squared. The samples were better distributed after y_5. This was a good indication of how difficult it was going to be to find a reliable model for y_1 for example.

6.3 DEVELOPMENT OF THE DATABASE

6.3.1 Procedures

6.3.1.1 Available methods using Minitab

The correlations between the independent variables were first examined. No pair or set of highly correlated variables (high - positive or negative - values for r) should be included. In effect, if two variables are highly correlated, then they will have the same influence on the model. Therefore, one of the two has to removed of the system. In this situation, the variable with the highest correlation with the dependent variable was chosen. This condition is called multicollinearity and is very common for economic data for example.

The process of choosing independent variables to suit best the regression model is referred to as the screening process. A different selection strategy can be adopted depending on the size of the sample, the number of independent variables and the accuracy required for the model. One strategy which can be applied generally is to include all independent variables and drop the most insignificant one (largest p-value > 0.05) each time until all remaining variables are significant ($p < 0.05$). This is called Backward elimination and can be done automatically by statistical packages such as Minitab.

This approach can be cumbersome if a large number of independent variables are present (e.g. 50 or more is not unusual is some studies). The variables can be entered one at a time and the model assessed at each stage with variables being chosen if significant ($p < 0.05$, $t > 2$ or $t < -2$) or removed if insignificant ($p > 0.05$, $t < 2$ or $t > -2$). This is known as the stepwise regression and can also be done automatically with Minitab with certain limitation (e.g. number of predictors limited to 20). Stepwise can be applied and the final recommended model can then be assessed fully using the other facilities of the package including residual plots. Another useful model available in Minitab is the Best Subsets Regression (BREG) model. It first looks at the all one-predictor models and selects the one with the largest R^2-value (Ryan 1994). It has to be noted that R^2 always increases as the number of predictors increases, because SSE always decreases as the number of predictors increases. Thus R^2 is not always the best value to look at when comparing models with different numbers of predictors. Adjusted R^2 takes into account the number of predictors in the model, using the following formula (Ryan 1994):

$$R^2 - \text{adjusted} = 1 - \frac{(\text{Error SS})/(n-p)}{(\text{Total SS})/(n-1)}$$

p is the number of predictors (+1 if the equation has a constant, which is the case for this study). Values for R^2 and Adjusted-R^2 were looked at carefully for each model.

6.3.1.2 Selected procedures

Because of the limitations of what can be done with Minitab, a specific selection procedure had to be put in place. The limitations greatly affecting our study were the number of independent variables that can be entered in any system (e.g. 20 for the best subsets). Another point of interest was the degree of freedom (DF) defined by:

DF = n - 1 - p

(Pindyck 1981)

This number should always be positive and bigger than 0. For example, if the number of samples is 57 and the number of predictors is 8, then the DF is 48, which is acceptable.

Taking into account the limitations of the package, the objectives of the database and the statistical requirements, the following procedures were adopted for each sample:

- correlations (Pearson) were calculated for all variables (see Figure 6.4). Variables with a correlation coefficient higher than 0.200 were selected to form an 'initial combination'. For each 'couple' (i.e. y_6 and a drilling parameter), two numbers are given: the correlation coefficient (top number) and the p-value (bottom number). The p-values must be lower than 0.05 for the predictor to be significant (this is the case for all the selected ones). This value represents the chance that this influence of the predictor is a 'coincidence'. Therefore, the lower this value, the more significantly it will influence the prediction of the 'y'. When the p-value is given as 0.000 in the outputs, it means that the value was too low to be represented;

```
Correlations (Pearson)

             Y6
Section   -0.410
           0.002

WBM       -0.516
           0.000

Tooth     -0.315
           0.017

PDC        0.211
           0.114

Oligocen -0.437
           0.001

>100      -0.299
           0.024

Depth      0.448
           0.000

Cell Contents: Correlation
               P-Value
```

Figure 6.4: The selection by correlation coefficient (for y_6).

- the initial combination was then entered as predictors in the BREG model (see Figure 6.5). They were usually entered by groups of four and the values of R^2 and R^2 were assessed. At that stage, the best combination was selected and the variables with no significant contribution (the ones with no 'cross' in the chosen combination) were removed of the model. At the end of this process, a treated initial combination was obtained with an R^2 usually higher than 30%;

Best Subsets Regression

Response is Y6

Vars	R-Sq	Adj. R-Sq	C-p	s	Section	WBM	Toth	PDC	Oligocen	>100	Depth
1	26.6	25.3	19.9	19.155		X					
1	20.1	18.7	26.4	19.991							X
2	43.4	41.3	5.3	16.981		X					X
2	42.9	40.8	5.7	17.054	X	X					
3	47.3	44.3	3.4	16.545		X			X		X
3	46.7	43.7	3.9	16.629	X	X			X		
4	49.0	45.1	3.7	16.422	X	X		X	X		
4	48.9	45.0	3.8	16.439		X		X	X		X
5	50.3	45.5	4.4	16.370	X	X		X	X		X
5	49.4	44.4	5.3	16.527		X		X	X	X	X
6	50.5	44.6	6.2	16.496	X	X	X	X	X		X
6	50.5	44.5	6.2	16.512	X	X		X	X	X	X
7	50.7	43.7	8.0	16.638	X	X	X	X	X	X	X

Figure 6.5: An example of the BREG model (for y_6).

- each single independent variable and its cross-products with other variables were then added again (usually four by four) to the model. The reason why 'four by four' was chosen was because it was faster than one by one and still possible with the limitation of 20 predictors. As previously, the combination with the highest R^2-value was selected and the variables giving no contribution were removed. Once all the variables were passed in the model, the whole process was carried out again, using the same principles. Finally, the best combination was obtained (see Figure 6.6).

Best Subsets Regression

```
Response is Y6

                                  D           S
                                  e   D D D L e   I O O O
                                  p D e e e o c I n l l l
                                  - e p p p g t n s i i i
                                  O p - - t - - s - g g g
                                W 1 - T J h s T - 1 - - -
            Adj.                B i 4 o u ^ e o 2 0 2 4 6
Vars  R-Sq  R-Sq   C-p       s  M g 0 o r 2 c o 0 0 0 0 0

   1  26.6  25.3  49.9  19.155  X
   1  17.9  16.4  62.1  20.260            X
   2  43.4  41.3  28.4  16.980  X         X
   2  43.2  41.1  28.6  17.005  X           X
   3  48.5  45.5  23.3  16.357  X X       X
   3  47.5  44.5  24.7  16.513  X X         X
   4  50.3  46.5  22.7  16.216  X X         X         X
   4  50.2  46.4  22.8  16.229  X X     X X
   5  56.0  51.7  16.7  15.409  X   X       X X X
   5  52.2  47.5  22.1  16.061  X       X   X X X
   6  57.7  52.6  16.3  15.260  X X X       X X X
   6  57.2  52.1  17.0  15.343  X   X       X X X       X
   7  59.8  54.0  15.4  15.029  X   X   X X X X X
   7  59.0  53.1  16.6  15.180  X X X       X X X X
   8  61.0  54.4  15.8  14.960  X X X     X X X X X
   8  60.8  54.2  16.0  14.995  X X X   X X X X X
   9  62.9  55.8  15.1  14.740  X X X   X X X X X X
   9  62.0  54.7  16.3  14.915  X X X     X X X X X   X
  10  64.7  57.0  14.5  14.535  X X X X X X X X X X
  10  64.1  56.3  15.4  14.654  X X X   X X X X X X   X
  11  66.2  57.9  14.4  14.380  X X X X X X X X X X   X
  11  64.7  56.1  16.5  14.688  X X X X X X X X X X     X
  12  67.2  58.3  14.9  14.312  X X X X X X X X X X   X X
  12  66.4  57.2  16.1  14.497  X X   X X X X X X X X X X
  13  69.3  60.1  14.0  14.007  X X X X X X X X X X X X X
```

Figure 6.6: An example of the final combination using BREG model (y_6).

- the best combination was then entered in the multiple regression model (see Figure 6.7). In this output, a large amount of information was given (see Appendix 8). For the purpose of these procedures, only the necessary information is shown in Figure 6.8. The rest of the data was analysed in section 3.4.2. In Figure 6.7, the first line represents the correlation between y_6 and its predictors. Later, the values for R^2 and Adjusted R^2 are given (in this case, 69.3 % and 60.1% respectively). Here, it can be noticed that the values found for R^2 is the same as in the previous output (which is expected). Finally, the last piece of information is the list of outsiders: either points with too much influence or points which have been left out of the model. This list was used for the next step in the development of the database;

```
Regression Analysis

The regression equation is
Y6 = 243 - 58.8 WBM - 0.0884 Dep-Olig + 0.00506 Dep-40 - 0.0150 Dep-Too
- 0.00567 Dep-Jur + 0.000002 Depth^2 - 159 Log-sec + 3.83 Sect-Too +
38.8 Ins-20 + 93.7 Ins-100 + 37.8 Olig-20 + 56.7 Olig-40 +
58.3 Olig-60

S = 14.01        R-Sq = 69.3%      R-Sq(adj) = 60.1%

Unusual Observations
Obs          St Resid
 14             * X
 15             * X
 16          -3.04R
 20             * X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.
```

Figure 6.7: An example of the output from the multiple regression model (y_6).

The aim was to find a suitable regression model: one with few relevant predictors and a good predictive ability. Therefore, the most important output on the printouts from the regression analysis was presently: R^2 and the p-value for each independent. It is reminded that here, the criteria were:

- R^2 with a minimum value of 80.0% (which is the minimum acceptable in our case), and;
- p-value with a maximum of 0.05 (which is the usual threshold). However, there is one exception. The p-value for the constant has to be interpreted differently: here it only shows how much the constant differs from 0. For example, a low p-value for the constant simply means that the constant is actually a large number. This was the case for y_6.

Then, keeping the same combination of independent variables in the regression model, some outsiders were taken off to increase the accuracy of the model. This process has to be carried out very carefully as it could decrease dangerously the robusteness of the obtained model. It was decided that the substraction of seven observations for each sample was a reasonable figure. This number was not big enough to change the entire orientation of the model and was high enough to significantly improve the accuracy of the model. Two ways were available to choose the outsiders that needed to be removed from the system:

- outsiders are indicated under 'unusual observations' at the end of the printout giving the results from the regression analysis (see Figure 6.7), or;
- outliers and high influence values can be noticed on the residual plots and 'Brush (under 'Editor') can be used to 'finger' the points and indicate the row numbers.

It was noticed that the best improvement in the model was obtained by using the first method rather than the second one. Usually, substraction of high influence values would decrease the value of R^2. The results obtained from the described procedures are presented in the next section.

6.3.2 Results from the statistical analysis

6.3.2.1 Failed tests

The regression analysis outputs for each sample are provided in the Appendix.8 and a summary is presented in the next section. The average R^2- value was 85.88% and 81.6% for the Adjusted R^2-value. These values were satisfying and guaranted a model of acceptable accuracy. Each residuals plots was also assessed and several anomalies were noticed: three samples failed three different tests (see Appendix.8):

- y_2 failed test 5;
- y_5 failed test 7, and;
- y_6 failed test 2.

In the case of samples y_5 and y_6, this failure only means that the residuals are amazingly low for a significant part of the sequence. This is usually not a problem for the model, on the contrary, it generally means that the fit is very good. It can become a problem if the number of residuals within zone C becomes suspiciously high. Then, this might come from a bad design in the experiments or non-random choice of the samples or a unsufficiency in the variety of samples. As far as sample y_2 is concerned, the failure could be more problematic as it meant some of the residuals were high. If this happens too often in the same sample, the model might have to be revised. However, generally speaking, the failures in our study were not numerous enough to cause any problem for our models and certainly did not induce any further treatment.

6.3.2.2 Summary of results

As stated before, all the results are gathered in Appendix.8. Table 6.3 shows a summary of the results found from the regression analysis outputs. It demonstrates that when the normality tests were bad for a dependent variable, a good model was difficult to obtain. In effect, when the normality test was predicting difficulty, the R^2 are usually low (e.g. for y_1). The contrary is also true, for example in y_7's case.

The lowest R^2 was given for y_1 and the highest for y_7. As a reminder, R^2 represents the fraction of the variation in y that is explained by the fitted equation. Adjusted R^2 is the same, but takes into account the number of predictors.

y	R^2	Adjusted R^2	Failed tests
y1	72.2	66.8	none
y2	88.1	82.9	no5
y3	85.2	81.0	none
y4	88.2	84.0	none
y5	87.5	83.4	no7
y6	88.4	84.1	no2
y7	95.4	93.4	none
y8	86.6	84.0	none

Table 6.3: Summary of the results from the regression analysis.

These numbers are one guarantee of the value of the models (see section 6.4.2).

6.3.2.3 Modelled equations

The obtained equations for the correlations between the independent and dependent variables are as below (see Appendix.8 for the complete information about every model):

- y1=0.87+14.0*quat+8.57*tooth*r20+0.00947*depth*cret-23.6*mud*cret +7.68*insert*r20-0.000283*depth*sect+0.00273*depth*mud+0.00440*depth*r40

- y2=19.8-12.1*sect*insert-22.6*insert*r40+20.3*jur*r20+0.0113*depth*mud +284*insert-55.4*mud+67.8*tooth+0.0443*sect*sect-24.6*r40-31.4*r200-0.0349*depth*insert-0.0270*depth*too-0.0318*depth*olig-0.00791*depth*jur +0.0124*depth*r40

- y3=75.6-3.87*sect-36.7*mud-59.6*cret+4.24*sect*tooth+0.0287*depth*cret-0.0341*depth*olig-0.0110*depth*tooth+0.00463*depth*r40+0.0692*depth*r100-0.0439*depth*r200+34.8*insert*r20

- y4=147-247*mud-76.2*cret-67.6*r200+7.99*sect*mud+26.0*mud*tooth +22.5*tooth*paleo+42.0*jur*r20-0.00306*depth*sect-0.0415*depth*olig +0.0429*depth*cret+0.0282*depth*mud+0.0107*depth*insert+ 0.00490*depth*r40

- y5=188-198*mud-60.6*r200+5.73*sect*mud+0.0521*depth*cret 0.00347*depth*sect+0.0204*depth*mud+0.00658*depth*r40-0.0590*depth*olig-8.3*cret +31.6*tooth*paleo-3.13*sect*pdc+4.81*sect*jur

- y6=230-60.9*mud-0.126*depth*olig+0.00669*depth*r40-156*log1&- +5.39*sect*tooth +38.5*insert*r20+134*insert*r100+57.1*olig*r20 +73.7*olig*r40+90.2*olig*r60-0.0279*depth*tooth-0.00553*depth*jur +0.000003*depth*depth

- y7=369-26.0*sect-120*mud-143*cret+0.812*sect*sect+5.50*sect*cret+ 5.34*sect*r100+38.9*insert*r20-0.0474*depth*olig+0.0267*depth*cret +0.00830*depth*r40+1.78*sect*tooth+20.5*paleo*r20-0.00232*depth*sect+0.0209*depth*mud+0.884*sect*r60

- y8=91.7+34.3*r200-8.89*mud*cret+135*mud*jur-14.1*sect*jur+1.79*sect*r100-32.8*olig*r20-1.54*sect*mud-0.0126*depth*quat

- y9=100

These equations represent the relationship between the drilling parameters and the points on the size distributions curves. It can be noted that different predictors explained different dependent variables. The predictors in the presented equations are 'coded' (i.e. they are not represented by their full names but by an abbreviation of their names). This was just for ease in using the package and in writing the equations. These correlations were introduced in a Fortran 90 program which can be used to predict the size distributions when the drilling conditions are known. The computing program is described in the next section.

6.3.3 Fortran 90 program

6.3.3.1 Objectives of the program

The primary objectives of the program were to:

- ask the user for the required input data;
- treat some of this input data as dummy variables (i.e. transform the entered value by either 0 or 1);
- set up some obvious boundaries for each variable (by this statement, it is meant that the program will ask the user to reselect the variable if he/she did not enter a value from the given choice);
- calculate the values for the *ys* (using the modelled equations), and;
- return the values to the user.

After running the first program for a high number of combinations (some of them realistic and others quasi-impossible in real situation), it was discovered that the set of equations would not always give coherent data. This means that the series of y-values contained outsiders. Two types of outsiders were noted
as:

- values that were not in the range between 0 and 100, and;
- values that would not respect the constant increase.

It was then thought that the best way to deal with these outsiders was to conduct a linear interpolation to 'bring the outsiders back into a suitable line'. This is common practice for missing data or non-fitting values, and the equation for linear interpolation can be found in section 2.3.1.

In the present program (which is shown in Appendix.9), the linear interpolation is done in two stages: first the maximum value is found and tested to see if it is greater than 100. If it is greater than 100, then the value goes through a loop which interpolates this value using the upper and lower values. Therefore, it cannot be the maximum anymore. Nevertheless, the maximum can still be greater than 100. So all the modelled values are tested and interpolated until the maximum value is less or equal to 100. Then, the values are orderly tested for constant increase. If any of them does not respect the increasing order, then it is interpolated using again the lower and upper value. Therefore, additional objectives were necessary in the program, there were to:

- test the calculated values and see if they are either negative or above 100 (they should not be as they represent a cumulative weight);
- notify the user if some modelled values are in the described case, advising him/her to change the combination (if possible) if more than 3 of them were outsiders.
- find the maximum and interpolate if greater than 100;
- do this until all the values are smaller or equal to 100;
- test all the modelled values for increasing order and interpolate until values are in increasing order, and;
- return the values to the user and advise the user to use the new drag correlation for transport problems.

6.3.3.2 Algorithm

In the following algorithm (see Figure 6.8), the common code was applied:

- square boxes are for actions;
- diamond boxes are for conditions;
- 'yes' and 'no' after a statement shows what the program does in each case, and;
- ellipsoid boxes are for 'start' and 'finish'.

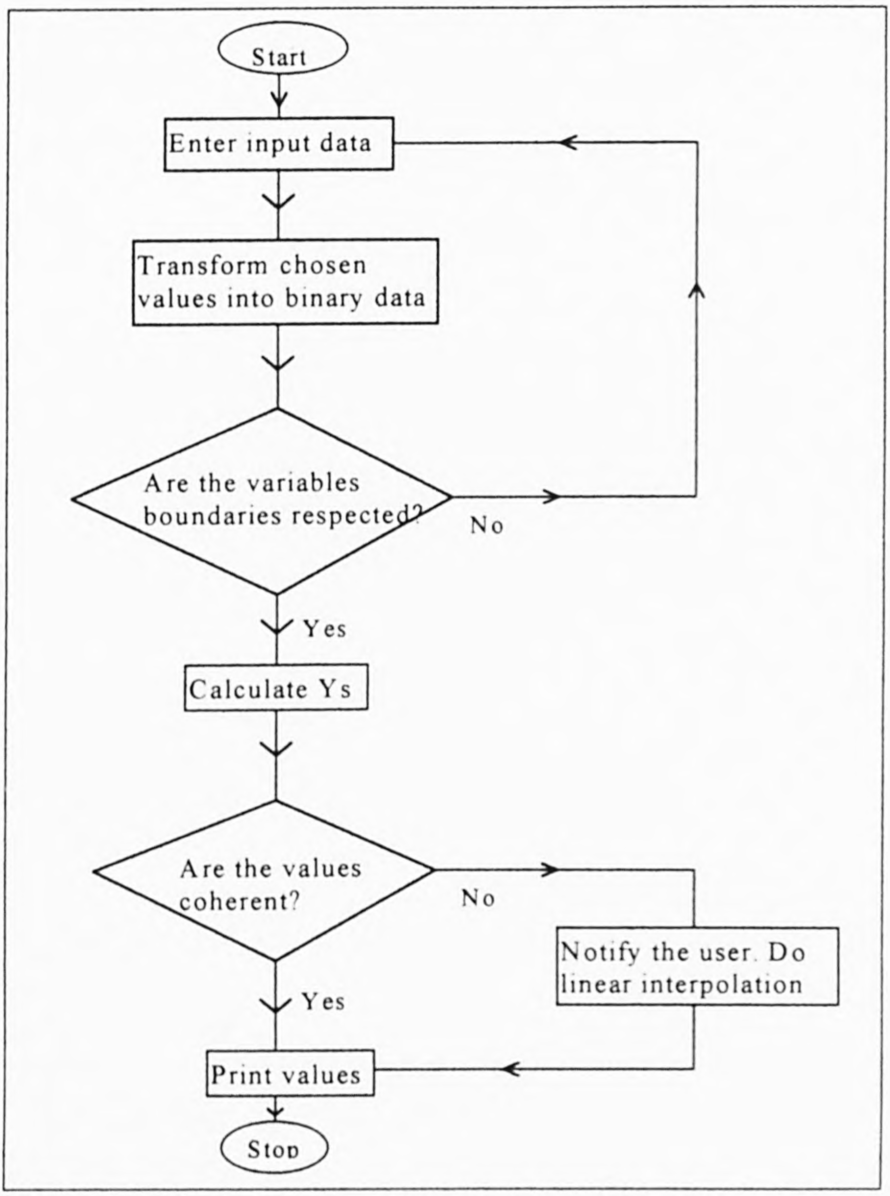


Figure 6.8: The algorithm for the Fortran 90 program.

This algorithm shows the steps of the program with the conditions which need to be satisfied to go from one step to another. The full program is shown in Appendix.9 with comments reminding the presented structure of the algorithm.

6.4 RESULTS FROM THE DATABASE

6.4.1 Examples of program runs

The program asks the user for the drilling conditions for each different combination. If the bit changes in the same section and stratigraphy, then the program has to be run again. The user enters his/her choice and presses 'Enter'. When all the choices are entered, the user is then notified about the 'outsiders'. Finally, the values for the size distributions are given to the user. An example of a run is shown in Figure 6.9.

```
Enter the section, the available choice is:
 23.5, 17.5, 12.25 and 8.5 (inches)
17.5

 Enter the stratigraphy drilled in that section
 If there are several stratigraphies in the same section,
 you need to run the program for each of them
 1- Pliocene, 2- Miocene, 3- Oligocene
 4- Eocene, 5- Paleocene, 6- Cretaceous
 7- Jurassic, 8- Triassic, 9- Quaternary
6

 Give the average depth (TVD in meters) for that combination
 (with a minimum value of 0m)
3000

 In this case, which drilling bit is used
 1- Tooth, 2- Insert, 3- PDC
2

 In this case, which mud is used?
 1- WBM, 0- SBM
1

 Enter the expected ROP for that stratigraphy:
 1- 0/20  2- 20/40  3- 40/60  4- 60/100  5- >100
2

 From the calculations, 1 y value(s) is(are) negative
 and 0 y value(s) is(are) greater than 100, therefore the interpolation
  will significantly influence the output data. If more than 3 values
  are in this case, you are advised to change your combination.

 The values for the cumulative weight curve are:
 x-value:  4.0 correspondent y-value:  12.212501
 x-value:  3.35 correspondent y-value:  21.679533
 x-value:  2.0 correspondent y-value:  41.341827
 x-value:  1.0 correspondent y-value:  63.07499
 x-value:  0.85 correspondent y-value:  65.07603
 x-value:  0.5 correspondent y-value:  69.74512
 x-value:  0.15 correspondent y-value:  77.79554
 x-value:  0.09 correspondent y-value:  81.1078
 x-value:  0.045 correspondent y-value:  100.0

 If you are dealing with cuttings transport. we advise you to use
 the following drag correlation applied to drill-cuttings:

 Cd = 24/Rep + 39.88/exp(4.54 * Sph)

  Please note that Rep is the Reynolds number of the particle and
 that Sph is the sphericity factor. According to Chien 1994, for
 most drill-cuttings, the average Sph is 0.8 (0.7924). If you have
  the sphericity factor for each range of size, just enter it in Cd.
```

Figure 6.9: An example of the program run.

As it can be seen, the program is very straightforward and easy to use, and the outputs are clear. In the output, the user is also advised to use the new drag correlation presented in section 4.4. A selection of four examples was taken from the database to show outputs in different situations. The results are given in Table 6.4.

No of sample	Drilling parameters	Experim. y	Modelled y	No of sample	Drilling parameters	Experim. y	Modelled y
5	12.25	3.36	2.07	26	12.25	14.47	15.52
	WBM	6.90	3.14		SBM	25.95	26.45
	PDC	13.87	13.40		PDC	79.32	38.62
	Cretaceous	21.49	17.14		Cretaceous	90.17	84.01
	40/60	22.53	18.73		0/20	90.68	84.76
	2840	27.87	23.55		2440	90.91	88.65
		39.91	42.03			91.73	92.53
		49.91	63.95			92.41	96.80
		100.00	100.00			100.00	100.00
Average error:		1.68%		Average error:		2.99%	
No of sample	**Drilling parameters**	**Experim. y**	**Modelled y**	**No of sample**	**Drilling parameters**	**Experim. y**	**Modelled y**
11	17.5	23.34	5.13	43	17.5	0.28	0.00
	WBM	27.50	67.69		WBM	0.57	1.84
	Tooth	42.13	68.55		Insert	1.19	5.21
	Paleo	49.43	69.18		Cretaceous	16.31	21.54
	0/20	50.31	69.41		0/20	19.53	26.11
	1940	56.47	73.49		2050	24.88	26.29
		61.83	81.96			28.18	49.17
		70.39	84.89			32.59	55.86
		100.00	100.00			100.00	100.00
Average error:		14.34%		Average error:		8.17%	
Total average:		6.80%					

Table 6.4: The results from the four examples.

As it can be seen in Table 6.4, the average errors on the size prediction for the four samples are very different. The total average error on the four samples is 6.80% which is definitely acceptable. The program was run for every sample and the results are given in the next section. This accuracy is different than the concept of goodness of fit as the program is applying linear interpolation to the outsiders. However, the linear interpolation should not be expected to be very much needed for the prediction of distributions of samples from the database. It will be more needed for totally new combinations of predictors. Therefore, one could wonder about the total quality of prediction of the database. The next section deals with the diagnostic of the models.

6.4.2 Evaluation of the database

6.4.2.1 Validation difficulties

When a new database is created, one can wonder about its quality, accuracy and robustness. The accuracy of the prediction compared to the used data is easy to define as shown in Table 6.4. The quality of the database depends on the relevance, the quality and the representativeness of the used data. The robustness depends on the range of data used and also on its capacity to predict new combinations. It is straightforward (even if sometimes cumbersome) to prove the quality, accuracy and robustness of the models for the prediction of used data. However, it is much more difficult to test the same properties when new combinations are concerned. The only way to do so, is to conduct a validation.

Two options could have been used to validate the database:

- by splitting the available data into two sets: one used to develop the equations and one to validate them (this is usually done when a large amount of data is available), and;
- by creating new independent data after the correlations had been developed with the available data.

The first method was not selected at the time because of the limited number of data. If a number of samples had been taken out of the system, the R^2 values would have decreased in consequence. When the present correlations were found, it was not affordable to take out a significant (and representative) number of samples off the system. Therefore, this method (which is commonly used) was rejected for the validation of the models.

The second method was believed to be meaningful, if well-planned, in the present case. When such a method is used, representative samples need to be analysed. For example, it would not have been valuable to analyse only SBM samples to validate the models, since most of the database was based on WBM samples. The same would happen to the type of bits, section etc. Therefore, some oil companies were contacted to see if they would provide with new samples and data. Unfortunately, at the time, the oil industry was in crisis. Oil companies were merging, laying off and reducing budgets. The drilling operations were limited to the 'survival level'. Very few companies were drilling at the time. Some of the contacted ones were drilling it was either for confidential exploration wells, difficult wells or using SBM. Therefore, at the time, no new samples were available. There were still some WBM samples in boxes in the SMOE laboratories. But they were from one year to one and a half year old. It was thought that the sieving of these old cuttings would be meaningless for the present purpose. Therefore, the second method was also rejected.

Hence, a 'proper' validation (in the strict sense) could not be carried out. It was then decided that if the validation on new combinations could not be done, then a thorough 'diagnostic' of the models should be conducted. This was to guarantee that at least, the used data could be 'modelled back' with quality, accuracy and robustness.

6.4.2.2 Diagnostic of the database

The best assurance of the value of the database is its R^2 value (and also Adjusted R^2 value). In the present case, their important values are presented in Table 6.5 (see Table 6.3 for all values).

	R^2	Adjusted R^2
Lowest	72.2	66.8
Highest	95.4	93.4
Average	86.45	82.45

Table 6.5: Important values of R^2 and Adjusted R^2.

Usually, the R^2 value is a very significant evaluation of a single model. However, in the present case, there are eight different models involved, each with a different R^2 value. The model for y_6 for example can be used with more confidence than the one for y_2. But this is in general of course, because there might be some cases where y_2 model was closer to reality than the one for y_6. So, for a specific drilling case, each of the points of the size distribution curve is predicted with a different accuracy. The overall quality of the fitting curves is: 86.45% and 83.45%. The average values are important but the range of values (the difference between the lowest and the highest) is also significant. It seems that there is presently a large difference between the lowest and highest values. This could cause an irregularity in the quality of the prediction for one combination (it is reminded that the program has to be run for each different combination). However, it can be observed that the model for y_1 is really an exception (which was predicted by the normality test). If this value is taken apart, all the other values only vary in the range of 10%. Therefore, the quality of the models can be guaranteed by this acceptable 'goodness of fit'.

However, this acceptable 'goodness of fit' is a necessary condition but not sufficient. There are other statistical methods which can be used in conjunction with the R^2 values to check the validity of the models. These methods consist in checking the residuals plots, the fitted lines and the different p-values. For each model, the information was produced and is presented in Appendix.8. No model was considered acceptable until they met all the requirements for the residual plots (these requirements were described in section 6.3.1.4). This was another guarantee that the modelled correlations were of good quality and robust.

The fitted lines for each model were plotted to show the experimental y-values versus the fitting values. An example of the fitted line is represented in Figure 6.10.

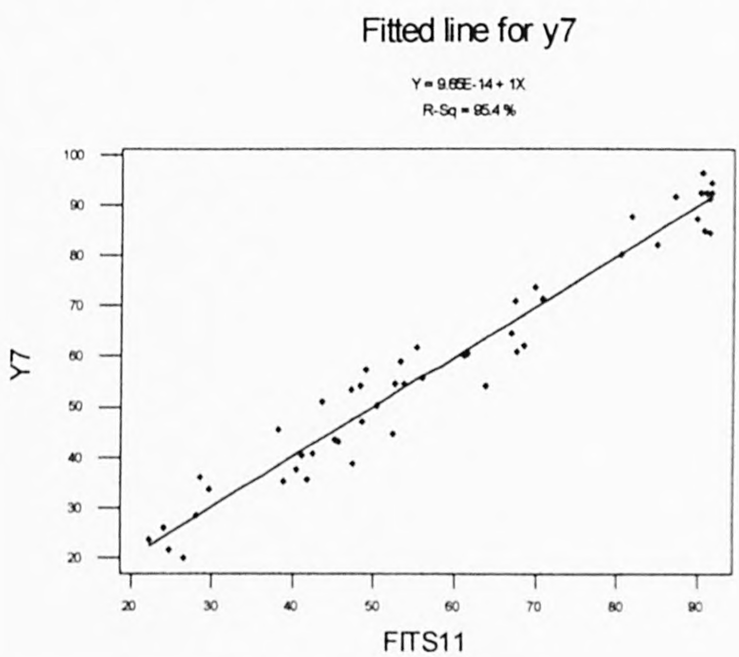


Figure 6.10: An example of a fitted line (for y_7).

The points on the plot are supposed to be as close to the line as possible, but also need to be 'well-distributed' along that line. Minitab give the equation for the plain line (which is the line of average value). The perfect case would be to obtain y = x. In the present case, the following equation was obtained:

$$y = 9.65\ 10^{-14} + x$$

As it can be seen in Appendix.8, all the models, had to pass all the tests to be considered acceptable. Once again, the fitted line for y_1 model was the least close to the perfect case.

Another good indication of the quality of the model is the p-value for each individual predictor and for the whole system. These values are present in the output from the regression analysis. The complete output is shown in the following Figure 6.11.

Regression Analysis

```
The regression equation is
Y5 = 188 - 198 WBM - 60.6 >100 + 5.73 Sect-Mud + 0.0521 Dep-Cret
           - 0.00347 Dep-Sect + 0.0204 Dep-WBM + 0.00658 Dep-40
           - 0.0590 Dep-Olig - 88.3 Cretaceo + 31.6 Too-Pale -
3.13 Sect-PDC
           + 4.81 Sect-Jur

Predictor        Coef       StDev          T        P
Constant       188.44       19.01       9.91    0.000
WBM           -197.88       35.95      -5.50    0.000
>100          -60.588       9.743      -6.22    0.000
Sect-Mud        5.729       1.355       4.23    0.000
Dep-Cret     0.052149    0.006296       8.28    0.000
Dep-Sect   -0.0034709   0.0005211      -6.66    0.000
Dep-WBM      0.020429    0.006232       3.28    0.002
Dep-40       0.006579    0.001594       4.13    0.000
Dep-Olig    -0.059010    0.007817      -7.55    0.000
Cretaceo       -88.27       12.86      -6.86    0.000
Too-Pale       31.593       6.507       4.86    0.000
Sect-PDC      -3.1290      0.5408      -5.79    0.000
Sect-Jur       4.8089      0.9974       4.82    0.000

S = 8.802       R-Sq = 87.5%     R-Sq(adj) = 83.4%

Analysis of Variance

Source            DF         SS          MS         F        P
Regression        12    19993.7      1666.1     21.51    0.000
Residual Error    37     2866.4        77.5
Total             49    22860.1

Source       DF      Seq SS
WBM           1      9076.9
>100          1      1186.3
Sect-Mud      1         1.7
Dep-Cret      1      2041.5
Dep-Sect      1        67.3
Dep-WBM       1       108.0
Dep-40        1       107.7
Dep-Olig      1      2309.8
Cretaceo      1      1844.1
Too-Pale      1       557.2
Sect-PDC      1       892.3
Sect-Jur      1      1800.9

Unusual Observations
Obs        WBM          Y5          Fit    StDev Fit     Residual
St Resid
 19       1.00        7.39        24.10         2.83       -16.70
-2.00R
 28       1.00       51.77        35.62         4.94        16.15
2.22R

R denotes an observation with a large standardized residual
```

Figure 6.11: The complete output from the regression analysis.

The p-values can be observed on the right hand side column under the modelled equation. For example, in the case presented in Figure 6.11, the p-values of each individual predictors are always smaller than 0.002 (the threshold being 0.05), with most of them equal to 0.000. This gives another guarantee that the model is good. It shows that every predictor has a significant influence on the correlation. It is reminded that when a predictor has a p-value of 0.002 for example, it means that there is 2 chances out of a thousand that its influence occurred by 'coincidence'. It is a 'security' that this predictor is of significant influence for most used data.

Another interesting p-value is the p-value for the whole system. It is seen in the 'analysis of variance' section in the right column called 'P'. The value in Figure 6.11 for example is 0.000. As it can be seen in Appendix.8, p-values for every models were equal to 0.000. This was again a good indication that the all the predictors used for all models were surely significant.

Moreover, the program was used to run all the 57 available combinations. The modelled results from the database were compared. Errors were calculated for the predictions of all the 'ys'. The average error for all the 'ys' was low: 2.19%. Table 6.6 summarises the findings of this analysis along with the R^2-values.

Variable	Error (%)	R-squared
y1	1.75	72.20%
y2	9.71	88.10%
y3	2.97	85.20%
y4	1.08	88.20%
y5	0.95	87.50%
y6	0.63	88.40%
y7	0.24	95.40%
y8	0.15	86.60%

Table 6.6: Errors on the 'ys' from the database.

It has to be precised that whenever any of the presented requirements was not satisfied by a model, the described procedures (see section 6.3.1.2) were run again to find a more valuable model. Therefore, the models obtained and tested are believed to be statistically and mathematically correct. They are also believed to fit the used data with an acceptable accuracy. The new correlations should be used in confidence for WBM and more prudently for SBM. It is valid for the conditions it implicitly and explicitly contains. However, it contains limitations (like any other model). The prime limitations are those induced by the generalisation of the data (e.g. only 3 types of bits).

6.5 SUMMARY

As stated in Chapter.1 and Chapter.2, there was an urgent need to define correlations between the drilling parameters and the cuttings size distributions. In Chapter.3, the cuttings size distributions were defined through experiments. In Chapter.4 and Chapter.5, the settlement of cuttings in water was analysed. A new drag correlation for irregularly shaped cuttings was developed. Chapter.6 presented the development of the correlations between selected drilling parameters and points from the size distributions curves. One model for each point was developed and carefully checked. Models were only judged acceptable if all the statistical requirements presented were fulfilled. A Fortran 90 program was created to support the database. It asks the user for input data, interpolates incoherent data and return values to the user. It also advises the user to use the new drag correlation for cuttings transport purposes. Finally, the program was run for every 57 combinations. Errors were calculated and their values were very low. The limitations of the database are inherent to the data used to develop it. More combinations would add more robusteness. Suggestions for further work on the database are presented in section 7.3.1.

Chapter.7
CONCLUSIONS AND RECOMMENDATIONS

7.1 OVERVIEW

The present work was divided in two main parts: the experimental work and the computational work. The computational work was conducted as an analysis of the experimental work. Contribution to knowledge on various subjects came from both approaches.

Chapter.7 concludes the present work. Conclusions on experimental and computing works are drawn. These conclusions lead to the need and recommendations for further work. These recommendations are based on ranging experiments conducted by the author or on information from the literature and specialists in the subject.

7.2 CONCLUSIONS ON EXPERIMENTAL WORK

7.2.1 Particle size and shape

In Chapter.1, the needs and requirements for the present study were presented. The EIA was described as well as existing cuttings dispersion models. It was stated that input data required for such models were not always relevant or in an adequate format for the user. Moreover, dispersion models are very sensitive to the settling speed equations. Therefore, this study concentrated on the characterisation of drill-cuttings and their aquatic settlement properties. Several potential applications of results were also listed, most of them involving cuttings transport in a fluid.

In Chapter.2, the relevant information about drilling and environmental engineering was presented. It showed in more depth the needs for studying the drill-cuttings characteristics and the correlations between these and the drilling parameters. In effect, existing dispersion models would be greatly improved if realistic sizes of drill-cuttings were taken into account. In order to do so, new correlations based on real drill-cuttings should link drilling parameters to particle sizes. In Chapter.3, the collection of offshore samples and drilling data is described. After organising this collection on North Sea offshore installations, experiments were carried in SMOE laboratories. In the laboratories, the sieve diameter of the drill-cuttings was measured and the shape assessed visually. The drilling parameters were known from the offshore survey and were put together along with the size distributions and the shape. The sphericity was defined using the available literature in association with observations. The laboratory experiments showed the limitations and accuracy of the present work. It proved the difficulties in dealing with real fresh samples. It questioned the validity of the work and its representativeness.

Supplementary data included drill-cuttings sizes and drilling data from the Norwegian sector, disaggregation information and the density of cuttings. The Norwegian data were provided from a similar analysis and were formatted before use along with the UK data. This data increased the total number of analysed samples to 57. Disaggregation tests were carried out as ranging experiments and are the support for some recommendations for further work (see section 7.4.1). The density was determined using given data from offshore and information from the literature.

Therefore, at the end of this work, a unique set of data was defined for each sample. This set of data was the base to develop the new database described in Chapter.6.

7.2.2 Particle settling speeds

During laboratory experiments described in Chapter.3, settling speeds of drill-cuttings were also measured. Single drill-cuttings were deposited in a water tank at ambient temperature and their settlement timed using two different techniques. A total of 187 measurements were carried out on cuttings with different shape and size. Speeds were plotted against size (a total of 30 points were obtained) and the graphs were analysed. Sources of errors were discussed and precautions to minimise the effects of these errors were listed. The settling speed values were the foundations of the work presented in Chapter.4 and Chapter.5.

In Chapter.4, the experimental values were compared to other experimental works as well as correlations values. Drag correlations were selected from the literature to represent the irregularly shaped particles. Two combinations of drag coefficients were defined for each particle. The values for the coefficient was then used to calculate the 'theoretical' settling speeds. These values were then compared to the experimental values. The comparison between all the data (i.e. experimental, 'theoretical', other experimental works and correlations) showed the coherence of the results and proved the need for a more adaptive drag coefficient correlation. This observation lead to the development of a new drag coefficient correlation using the experimental data. This new correlation was then analysed and compared with the most appropriate: Chien's correlation. There was an excellent agreement between the new correlation and Chien's correlation. A computational analysis was also carried out in Chapter.5.

7.2.3 Contribution to knowledge

The experimental work presented in this thesis was proved to be coherent and vital to improve existing dispersion models. Applications are varied and numerous ranging from environmental engineering to hole cleaning prediction. The main objectives were achieved to give sensible data on which to base to rest of the present work. The difficulties and limitations of the experiments were described and some of them were the base for recommendations for further work (see section 7.4).

The main contributions to knowledge from the experimental work are:
- the characterisation of real drill-cuttings (i.e. definition of their size and shape);
- the collection of drilling parameters for each analysed sample;
- the measurement of settling speeds of real drill-cuttings in water;
- the validation of the settling speed values, and;
- the development of a new drag correlation for irregularly shaped particles.

7.3 CONCLUSIONS ON COMPUTING WORK

7.3.1 The modelling exercise

Experiments measurements from Chapter.3 and analysis from Chapter.4 were the base for the modelling exercise. In Chapter.4, experimental settling speeds were validated against other experimental values, correlations for settling speed and drag coefficients. A new drag correlation was also determined. In Chapter.5, the comparison was made with computational values. A CFD commercial package was used to model the settlement of the particles. Four tests were run:

- a calibration test using the spheres form the validation exercise in Chapter.3 and the default drag correlation;
- test No1 using the first combination of drag correlations given in Chapter.4;
- test No2 using the second combination of drag correlations given in Chapter.4, and;
- test No3 using the new drag correlation developed in Chapter.4.

The 'calibration' tests showed firstly an excellent match between experimental and theoretical values for spheres. They also showed the need to use a drag coefficient better adapted to the shape of particles. Test No1 and Test No2 gave good agreement with the semi-theoretical values but results could be improved in comparison with the experimental values. Finally, Test No3 gave a low error on experimental values (19.07%). It proved that the drag coefficient was very well adapted to the shape and regime of the drill-cuttings. It also showed that the used CFD package was very sensitive to the drag coefficient. It demonstrated that it was a useful and powerful tool to predict the settlement of drill-cuttings into static water.

7.3.2 The new database

The needs for correlations between the drill-cuttings and drilling parameters were made clear and important, especially in the environmental engineering applied to offshore industry. Therefore, in Chapter.6, the drill-cuttings size distributions and corresponding drilling parameters were used to develop a new database. Correlations between selected drilling parameters and points on the cumulative distributions curves were found. Each point was then predicted by a function of the selected drilling parameters. A total of eight models was revealed. The equations were developed using a commercial statistical package. In order to check the validity and quality of the models, statistical techniques were used. The quality of fit obtained was higher than 85%, and all the residuals met the defined requirements. A Fortran 90 program was written to support the database and to facilitate the use of the correlations. The outputs of this program are the predicted points for the distribution curves when the drilling parameters are given. The outputs also advise on the use of the new drag correlation for drill-cuttings. The program was tested and improved until satisfaction. The 57 available combinations were run with the program to compare with experimental data. The average error on the prediction was amazingly low: 2.19%. Therefore, this database is believed to be of good quality and extremely useful for problems involving drill-cuttings and their transport.

The work carried out for the present study has already been incorporated into two commercial packages: Newcut and Proteus (BMT 1999) (see Appendix.10). For example, Proteus contains the defined correlations to predict the drill-cuttings size distributions when the drilling parameters are known. As it can be seen in Appendix.10, the interface is very user-friendly and the size distributions are given as one of the numerous outputs of the program. Then, the user can predict the dispersion of those cuttings by choosing the area, the time of the year etc. As far as Newcut is concerned, the Fortran 90 program developed by the author has to be used first and independently. Then, using the size distributions, the dispersion model can be run.

7.3.3 Contribution to knowledge

From the computing work, the contributions to knowledge are:

- a new correlation for the drag coefficient of drill-cuttings;
- a sensitivity analysis of a model predicting the settlement of particles to the drag correlation;
- a set of eight models capable of predicting the drill-cuttings size distributions when the drilling parameters are known, and;
- a program facilitating the use of the correlations and advising on the aquatic settlement properties of drill-cuttings;

The applications for the new database and new drag coefficient correlation are numerous and varied. The new database can easily be run independently of a package or can even be simply implemented to a package. The new drag coefficient is also very simple to introduce. As a conclusion, it is believed that the new database combined with the new drag coefficient is a very useful tool for any problem involving drill-cuttings. It has many applications and has already been incorporated into two different models. The work was only based on real offshore samples and data, which makes its originality. The results from the work were analysed in different ways (using commercial statistical and CFD packages and the literature review). They are believed to be of good quality and representative of the objectives. The main objectives of the overall work were satisfied and the work itself always stayed challenging and motivating. However, there is still place for improvement and further work.

7.4 RECOMMENDATIONS FOR FURTHER WORK

This section deals with recommendations for further work which are based on ranging experiments, available literature and specialists opinions.

7.4.1 Drill-cuttings characteristics

After conducting the sieving experiments and the development of the database, it was realised that more accuracy and more robustness could be obtained from further work. Further work on these subjects could broaden the scope by adding more combinations or even new drilling parameters. This would be very important for tackling problems in different parts of the North Sea (and eventually of the world) and using different methods of drilling (i.e underbalanced or coiled tubing). Therefore, some suggestions for further work are given below:

- more tests could be done to enhance the accuracy and robustness of the database;
- the database could be validated with a large number of combinations. After validation these 'new' combinations could be introduced in the database to enhance the accuracy and the robustness of the database;
- tests could be conducted for more and new drilling conditions (new drilling bits or muds);
- sieve analysis could be conducted with samples drilled under underbalanced conditions and also using coiled tubing drilling. It is believed that the cuttings size distributions would be drastically different than those of the present study, and;
- the present database could be introduced in packages to predict the dispersion of drilling wastes in the marine environment and also to predict hole cleaning.

As a summary, more drilling parameters and samples could be added to the existing system. For example, the weight on bit (WOB) is of influence in the hole cleaning process. According to May (1999), underbalanced drilling is a parameter that should be added to the database as more and more jobs are done in underbalanced conditions. Under these conditions, May suggested that the cuttings flake off more easily because of the difference in pressure and therefore are bigger and sharper for certain formations. All the samples used for this study were from wells drilled in overbalanced conditions. So, it would be an interesting project to compare samples from underbalanced drilling with overbalanced drilling. Of course, formations like soft sand or very soft clay might still not be affected by this parameter.

Improvement could be made on the drill-cuttings characteristics by measuring their size and sphericity in a different way than the present study. For example, Perez-Rosales (1969) proposed a practical method for determining true sphericity of irregular particles. It involved measuring the volume of the particle (by measuring the displacement of a liquid after submersion of the particle for example). It also needed the 'mean grain thickness' which is more laborious and requires a large number of particles. Other researchers tried to work on 'statistical characteristics' (i.e. average characteristics over a large number of particles). For example, Martin (1927/28) did some research about correlating the statistical diameter and volume with the surface of irregularly shaped particles of crushed sand. This type of correlation might help in determining with more accuracy the sphericity factor of drill-cuttings. However, it is noted that the relationship proposed by Martin (1927/28) is only suitable for a large concentration of particles.

As a conclusion, there are still a large number of studies which could be carried out on this fascinating subject. The oil industry would surely benefit in many different ways from a better knowledge of the drill-cuttings characteristics.

7.4.2 Disaggregation tests

As stated earlier, disaggregation can significantly affect cuttings size distributions. Therefore, it is felt that more information in this area would improve the general knowledge of cuttings behaviour in different fluids. Studies of disaggregation of cuttings in fresh water, seawater but also in drilling fluids would help to design cuttings treatment and predict cuttings dispersion and hole cleaning. It might also be of great importance for the choice of mud composition. The disaggregation tests were only 'ranging' experiments (see Appendix.4). From the tests run offshore, some recommendations can be made as follows:

- experiments should be done on more samples with different types of clays
- experiments should be done on drill-cuttings still muddy (to see the influence of the drilling mud on the disaggregation processes) as well as rinsed (in reality cuttings are rinsed in a certain extent by the seawater flush before discharge).

- tests under dynamic conditions should be studied further and procedures to represent different turbulent ambient conditions should be investigated (set up a 'mechanic' way to do so, like using a shaker that would produce in the ambient fluid approximately the same Re)
- then particles resulting from disaggregation tests should be sieved again - if there was any change in their structure of course.
- finally, new cuttings size distributions can be drawn and maybe a coefficient of change in the size distributions under various conditions can be obtained which would be easily introduced in the existing database. The modified database might require additional input data from the user in order to correlate with the coefficients of change in the cuttings size distributions.

7.4.3 Drill-cuttings settlement

In the present work, settling experiments and modelling were presented. However, as far as the settling experiments are concerned, more work could be conducted to study the effect of concentration of particles for example. Another interesting subject is the influence of disaggregation and aggregation processes of the settling of drill-cuttings in seawater. The combination of those and concentration of drill-cuttings would be a complex but fascinating project. More settling experiments could be conducted as it would be useful to conclude on a larger number of settling speeds curves. If the sphericity of particles is known with accuracy, the conclusions would especially be valuable. This would require setting up experiments to measure several characteristic lengths or the volume of particles. Once these are known, then the sphericity can be calculated rather than defined from visual assessment. An accurate assessment of the density would also make the settling speeds curves more meaningful.

As a conclusion, as far as improvement of the present work is concerned, more measurements could be taken on more samples. The combination of different techniques (e.g. video recording and laser measurement) could improve the accuracy and the range of particles sizes used for the settling experiments. Settling experiments could be conducted in drilling muds or completion fluids with different properties. New drag correlations could be found for each specific drilling mud. A better knowledge of drill-cuttings settlement could tremendously improve the accuracy of dispersion models and hole-cleaning prediction models. It is felt important by the author that any further work should be carried out using real fresh drill-cuttings. Nevertheless, it should also take into account the fundamental physics regarding the settlement of irregularly shaped particles. As stated in Chapter.4, some researchers have conducted some experiments but never on a large number of real drill-cuttings, measuring their size, shape and density prior to the settlement. The study of the characteristics and settling properties of offshore drill-cuttings is an endless and fascinating subject. There is a large scope of work to improve and strengthen the present study and further develop the subject.

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APPENDICES

APPENDIX.1: OFFSHORE SURVEY DOCUMENTATION.

The following document is addressed to the Company Man

CUTTINGS DISPERSION MODELLING PROJECT

INTRODUCTION

This project is for a PhD as well as for a research project involving 4 British universities and 6 oil companies. The final aim is the development of a computational model to predict the physical dispersion of drilling wastes into the sea. To get the input data for the model we need to develop a database containing the drilling parameters and the drill-cuttings characteristics (i.e. size, shape, density, nature of the rock). In order to get this database we need to put together the drilling parameters and the characteristics of the cuttings for the corresponding drilling parameters. To do so, and if agreed, the logger should fill in the tables shown in the following document.

In this table, the drilling parameters are required first and then the characteristics of the cuttings are monitored. Each time there is a change in the type of bit, formation, shakers screens, section or drastic change in the ROP and RPM, a sample should be taken from each scalper and shaker. The man in charge of the shakers should take a sample from each of the shakers and scalpers for the same amount of time, in order to take the different discharge rates into account. The content of all the subsamples should be mixed up together and a representative sample taken. The shape (Angular/Flat/Round) and the size of the cuttings should be looked at and recorded in the table. This determines the correlations between the drilling parameters and the characteristics of the cuttings. However, if you see a big change in the cuttings characteristics even if one of the parameters listed above has not been changed, please do not hesitate to take a sample and analyse it. The data for a complete well should be recorded on the same floppy disk (please, make a back up just in case!). Then the floppy should be given to you.

Thank you very much for your time and help. I really appreciate it!!!!!

METHODOLOGY

1- 2 floppy disks containing the tables + the methodology are sent to the Company Man on the rig.

2- The Company Man sends the 2 floppy to the logging unit.

3- The logger fills in the table during the entire duration of the well. The table only needs to be filled in when there is a change in one of the following drilling parameters:
  - change of bit or use of a turbine
  - change of formation
  - change of section
  - important change in the ROP or RPM
  - change of shakers/scalpers screens.

4- Roughly speaking, the table should be filled in each time there is a change in the characteristics (size, density and shape) of the drill-cuttings.

5- So, each time there is a change in the drilling parameters, a sample should be taken as described in the methodology contained on the floppy, then analysed. This would be done at the same time as usual sampling and analysis and should therefore not disturb the usual routine of the logger. The data is then recorded in the tables. A back up is made regularly on the second floppy.
6- Once the well is completed, the 2 floppies are sent back to the Company Man who will then send them back to the following address. The Company Man should also send the Fluid Phase Reports (summarising most of the drilling parameters for each phase) along with the Well poster.

Linda Carles
SMOE
The Robert Gordon University Tel: 01224 262 310 Fax: 01224 262 333
Schoolhill email: merljc@mechfs3.rgu.ac.uk
ABERDEEN AB10 1FR.

The following document is addressed to the mud-logger

CUTTINGS DISPERSION MODELLING PROJECT

INTRODUCTION

This project is for a PhD as well as for a research project involving 4 British universities and 6 oil companies.
The final aim is the development of a computational model to predict the physical dispersion of drilling wastes in the sea.
To get the input data for the model we need to develop a database containing the drilling parameters and the drill-cuttings characteristics (i.e. size, shape, density, nature of the rock). In order to get this database we need to put together the drilling parameters and the characteristics of the cuttings for the corresponding drilling parameters. To do so, and if agreed, the logger should fill in the tables shown in the following document.
In this table, the drilling parameters are required first and then the characteristics of the cuttings are monitored. Each time there is a change in the type of bit, formation, shakers screens, section or drastic change in the ROP and RPM, a sample should be taken from each scalper and shaker. The man in charge of the shakers should take a sample from each of the shakers and scalpers for the same amount of time, in order to take the different discharge rates into account. The content of all the subsamples should be mixed up together and a representative sample taken. The shape (Angular/Flat/Round) and the size of the cuttings should be looked at and recorded in the table.
This determines the correlations between the drilling parameters and the characteristics of the cuttings. However, if you see a big change in the cuttings characteristics, even if one of the parameters listed above has not been changed, please do not hesitate to take a sample and analyse it.
The data for a complete well should be recorded on the same floppy disk (please, make a back up just in case!). Then the floppy should be given to the Company Man.

METHODOLOGY

1- The table is read first in order to understand the data required. Most questions should be answered in this methodology, but if you have more, please contact your Company Man.

2- When a change occurs in the following drilling parameters please take a cuttings sample (method to follow) from the shakers room, analyse it and fill in the tables:
   - change of bit/ use of turbine
   - change of formation
   - change of section
   - important change in ROP or RPM

3- When a change occurs the solids/mud loss control inspector should take a tenth of the content of the trail from each shaker and scalper when he measures the rate of discharge. Each of these 'tenths' are placed in a bucket and stirred gently. Then, three cups of this material are given to the logger who can then carry on the analysis. Once every two or three sampling procedures (not routine), two bags (the ones used by the logger to send samples to the companies) should also be sent to us.

4- The 3 cups and the bagged samples are brought to the logging unit. The 3 cups are then analysed as follows:
   - mix the 3 cups together
   - weigh the total sample
   - wet-sieve them with the sieves you've got on board
   - weigh each of the category of sizes

That gives you an idea of how much you have from each size so now you can fill in the lower part of the table.

5- For each different size check the most common shape of cutting and add A/F or R when needed.

6- The drilling parameters in the upper part of the table should be filled **at the lag length** so it corresponds to the parameters at the time the sampled cuttings were drilled.

7- The total length of section is obviously given at the end of the section.

8- The size of the screens can be given by the mudman and should not change very often over a well.

9- In the comments part, please do not hesitate to put any difficulty you had with filling in the table or if something unusual occurred during the drilling of the well.

10- 6 sheets (the first one is an example) ready to use (one per section) are available to you, but if you need more, just add as many as you want.

11- Regularly, please, make a back-up on the 2nd floppy disk.

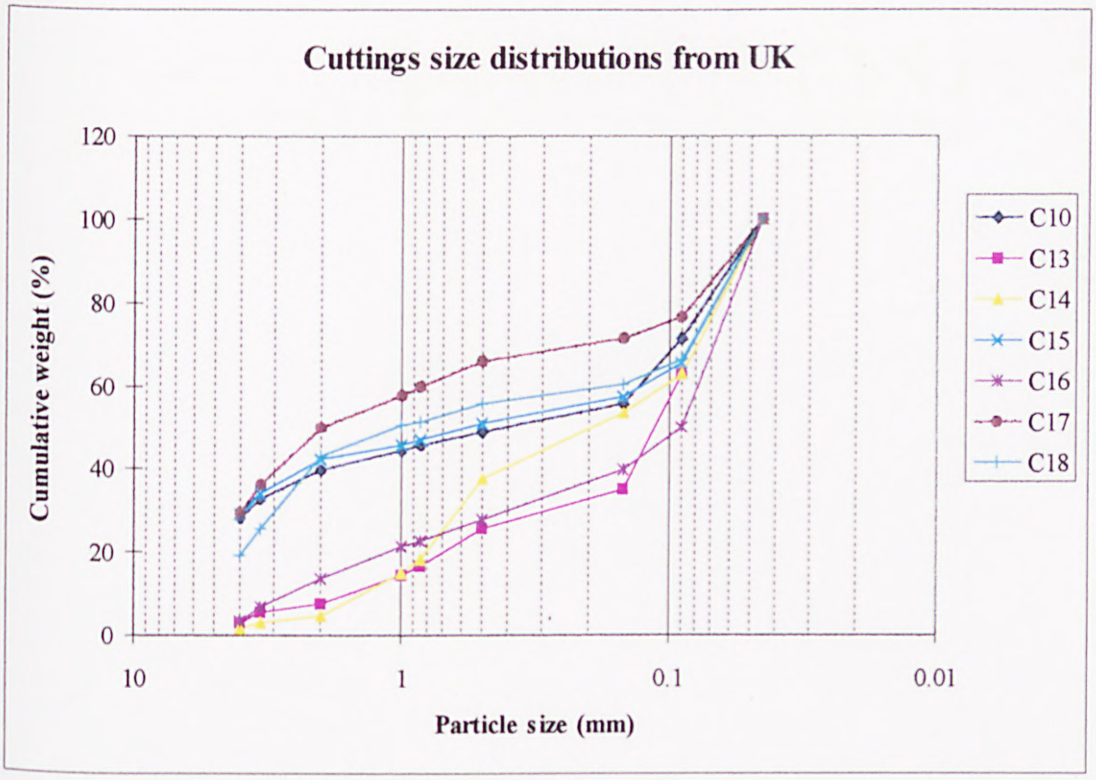
12- The bagged samples should be sent as soon as possible **along with** the corresponding drilling parameters.

13- Please, do not forget to specify the point of discharge!

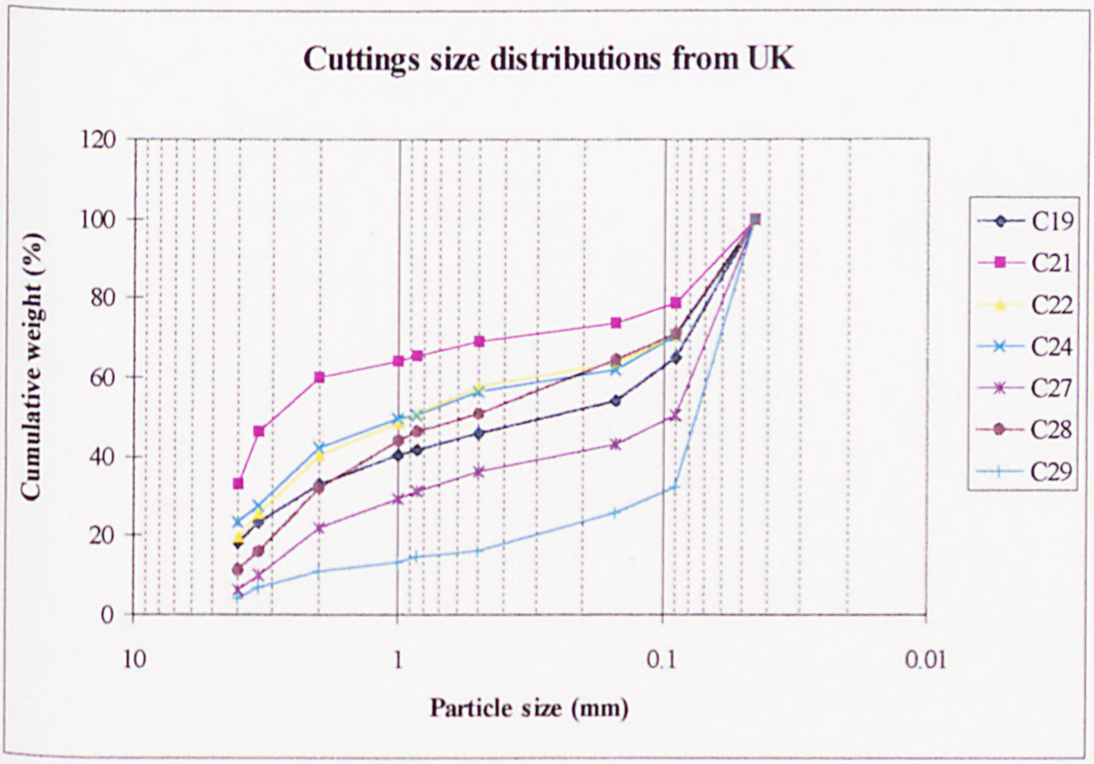
I thank you very much for your time and help. This data is really crucial for me so I really appreciate this!

Thank you very, very much!!!!!

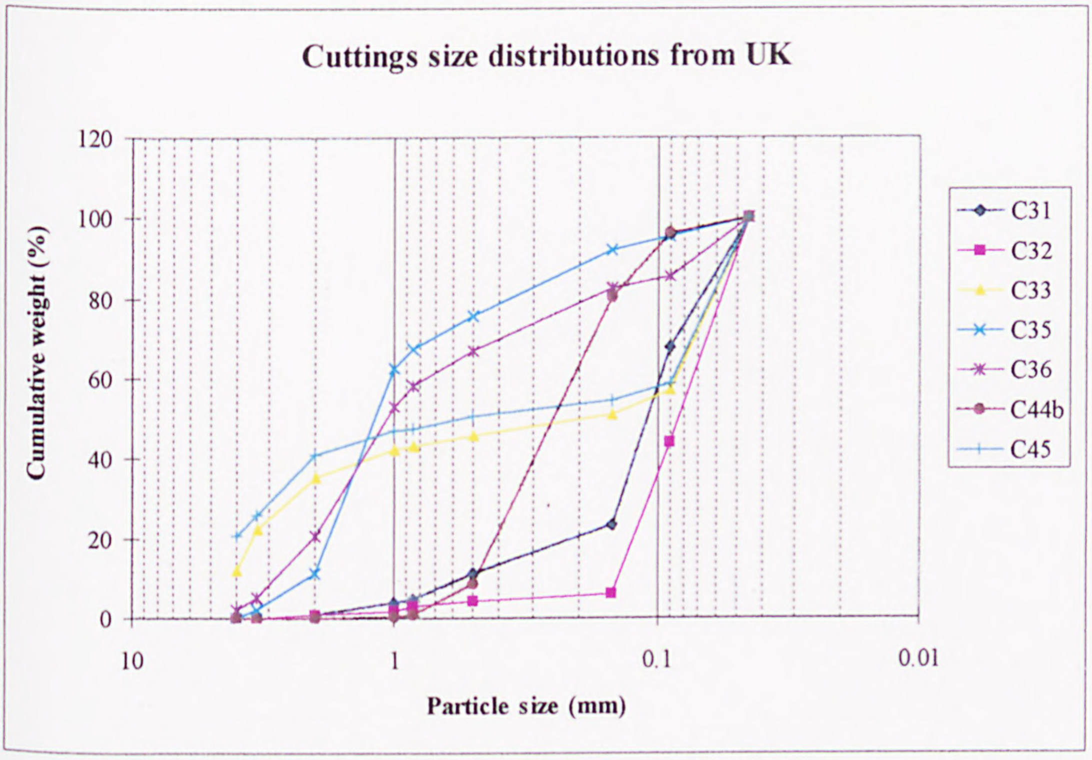
APPENDIX.2: SIZE DISTRIBUTIONS FOR ALL SAMPLES.

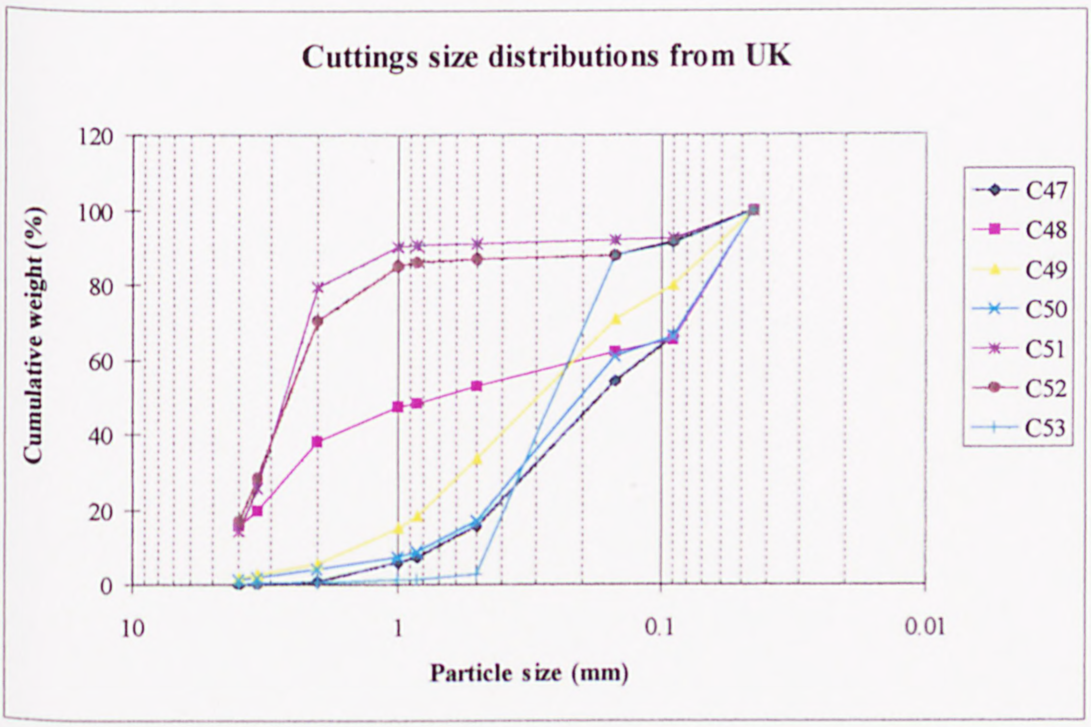


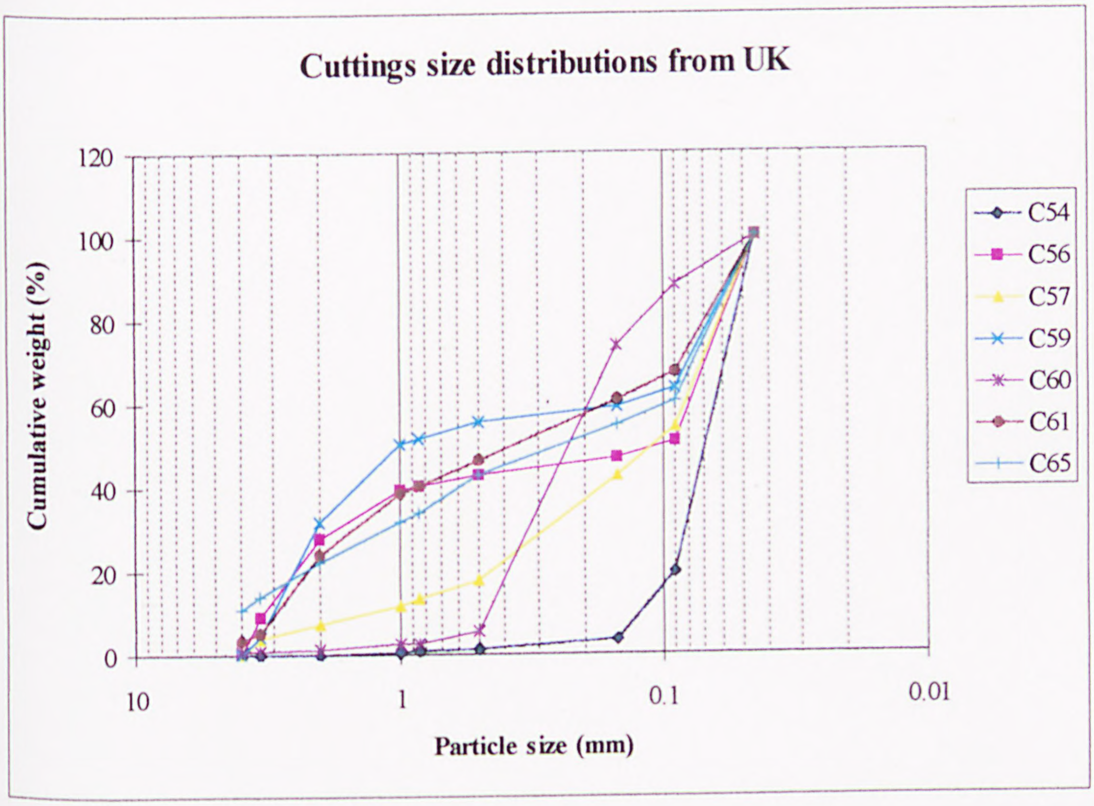
Cuttings size distributions from UK
Cumulative weight (%)
120
100
80
60
40
20
0
10
1
0.1
0.01
Particle size (mm)
C10
C13
C14
C15
C16
C17
C18

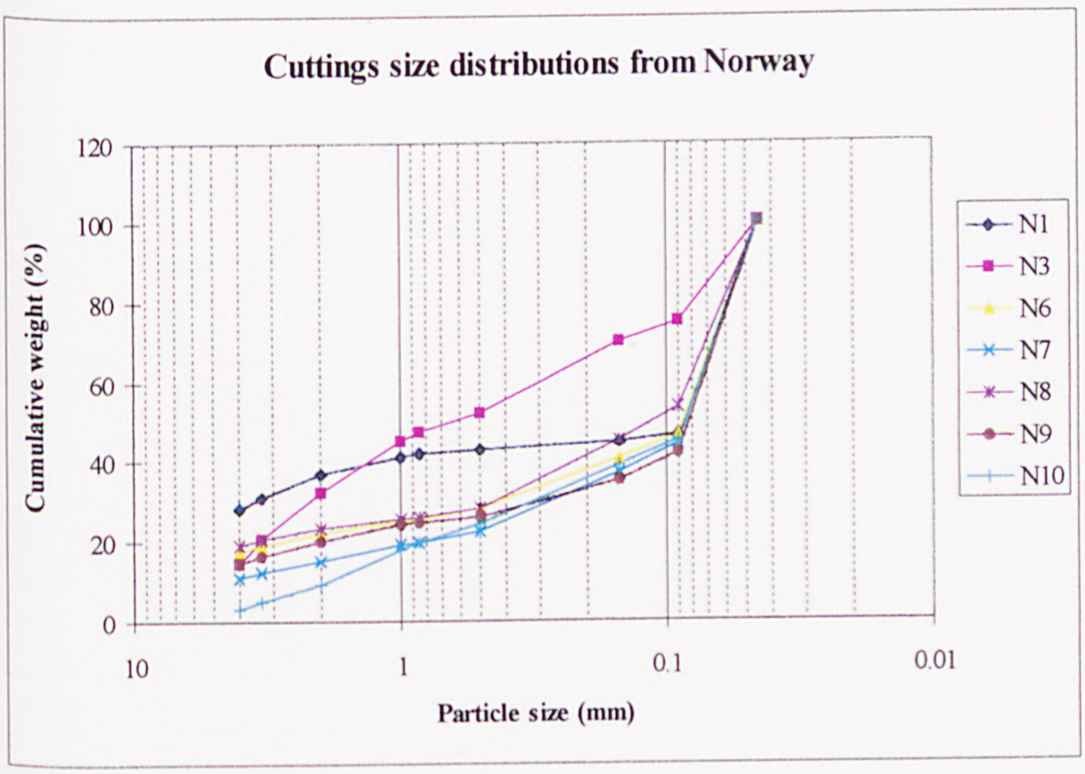


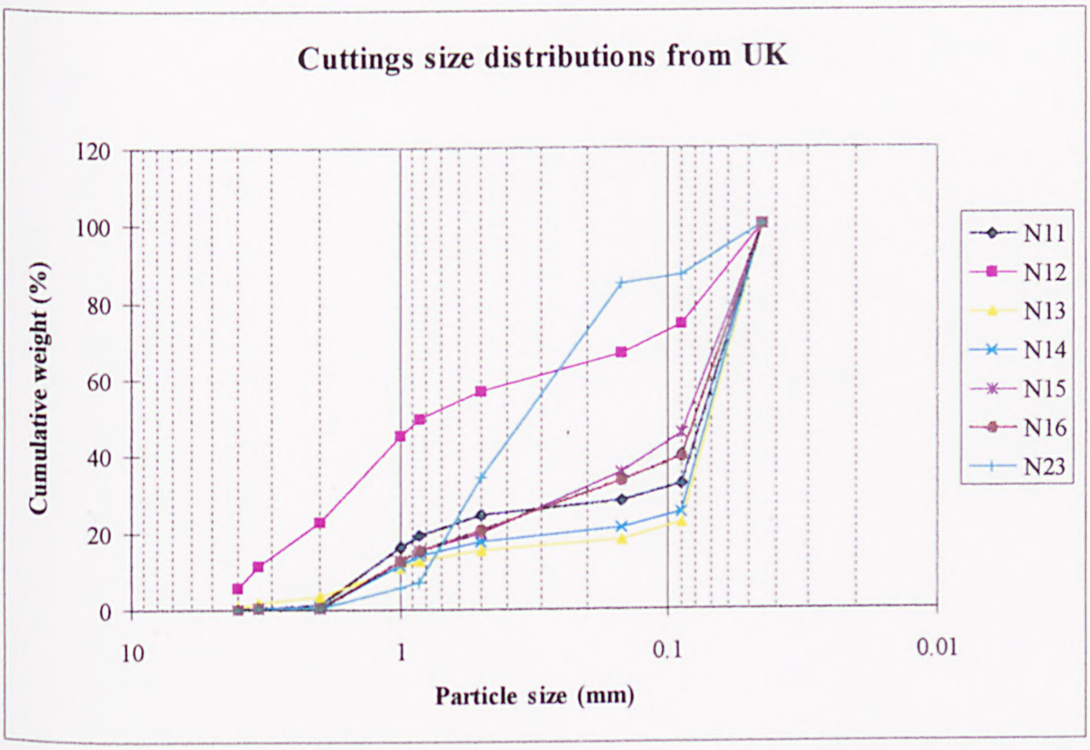
Cuttings size distributions from UK
Cumulative weight (%)
120
100
80
60
40
20
0
10
1
0.1
0.01
Particle size (mm)
C19
C21
C22
C24
C27
C28
C29

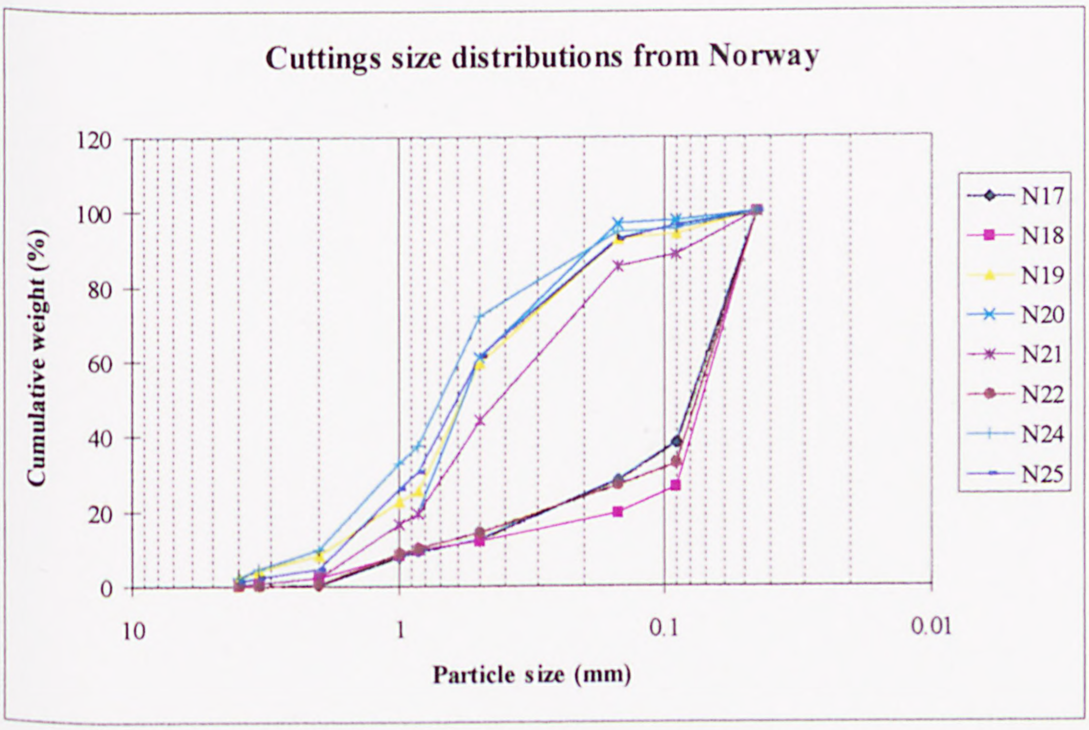

Cuttings size distributions from UK
Cumulative weight (%)
120
100
80
60
40
20
0
10
1
0.1
0.01
Particle size (mm)
C31
C32
C33
C35
C36
C44b
C45


Cuttings size distributions from UK
Cumulative weight (%)
120
100
80
60
40
20
0
10
1
0.1
0.01
Particle size (mm)
C47
C48
C49
C50
C51
C52
C53


Cuttings size distributions from UK
Cumulative weight (%)
120
100
80
60
40
20
0
10
1
0.1
0.01
Particle size (mm)
C54
C56
C57
C59
C60
C61
C65


Cuttings size distributions from Norway
Cumulative weight (%)
120
100
80
60
40
20
0
10
1
0.1
0.01
Particle size (mm)
N1
N3
N6
N7
N8
N9
N10


Cuttings size distributions from UK
120
100
80
60
40
20
0
Cumulative weight (%)
10
1
0.1
0.01
Particle size (mm)
N11
N12
N13
N14
N15
N16
N23


Cuttings size distributions from Norway
120
100
80
60
40
20
0
Cumulative weight (%)
10
1
0.1
0.01
Particle size (mm)
N17
N18
N19
N20
N21
N22
N24
N25

APPENDIX.3: DISAGGREGATION EXPERIMENTS.

Background

First of all, for most oceanographers, 'flocculation' and 'aggregation' (as well as 'deflocculation' and disaggregation') can be used interchangeably. The word 'coagulation' also refers to a similar phenomenon but generally has the connotation that the process involves particles in the colloidal size range (Muschenheim 1997 and Fennessy 1997). Estuarine research has tended to use 'flocculation' while shelf seas and deep ocean research uses more (marine) aggregation for their terminology. Aggregation (and therefore disaggregation) involves mostly mineral grains much larger than few microns (clay size) (Fennessy 1997). However, it is understood that for pure sedimentologists and chemical engineers, some of these processes are different if looked in detail. In the present case, flocculation was not of primary concern. Disaggregation was certainly the main interests in this short study of the phenomenon.

The subject of disaggregation and aggregation processes have been extensively studied in the sedimentalogy field, and especially for estuaries by for example: Fennessy et Al 1994a, Fennessy et Al 1994b, Gibbs 1985, Muschenheim and Milligan 1996, Van Leussen, Eisma 1986, Lick et Al 1993, Fennessy and Dyer 1996, Muschenheim et Al 1995. One statement that could be useful for the prediction of the hole cleaning for example, is by Lick et Al (1993): the relationship between a floc (or an aggregate) velocity and its diameter is non-linear because the floc density decreases as the floc gets larger. Gibbs (1985) also studied the velocity of flocs as a function of their diameter and gave a simple relationship for pure clay minerals an fresh water. When disaggregation changes the initial size distribution, the reverse process should not be neglected. If big particles disaggregate into fine particles, it is very likely that they will re-aggregate to form bigger particles again. The density of these new particles will probably be different than that of the initial particles (Gibbs 1985). However, these processes are very difficult to observe and measure in situ. New methods to measure aggregation, break-up and characteristics of flocs have been found. Tsao and Hsu 1989 developed an interesting model to describe the floc breakage. They included in their model the non-conservation of the floc's volume when breakage occurs. But, as far as the present litterature research is concerned, there was no study found on these problems directly related to real drill-cuttings from the North Sea.

For the purpose of the present study, it would be useful to know the changes in size distributions occurring when drill-cuttings disaggregate or re-aggregate in the seawater. The size distributions given from the laboratory experiments have been determined from samples coming directly from the shale-shakers. Therefore, if any disaggregation or re-aggregation happened on the way back from the hole to the surface, it has been somehow taken into account in the experimental size distributions. However, these size distributions might be completely different after impact with the sea surface (if the discharge is done above the sea surface) or simply because of the contact with seawater. Some processes will make the particles smaller and others bigger. Eventually, there is maybe a balance in the size distributions that could allow the whole problem to be neglected. It would be very interesting to know for WBM cuttings discharged in the North Sea. The author believes that the processes will depend on the following parameters:

- the initial cuttings size;
- the characteristics of the cuttings;
- the concentrations of the cuttings in the studied area;

- the ingredients in the drilling mud and its rheology;
- the properties of the seawater (chemical, physical and biological), and;
- the physical conditions of the two flows (the discharge and the water column), especially turbulent conditions.

Equipment

These experiments were conducted on the fixed platform the 'North Alwyn' operated by Total Oil Marine plc in the Northern North Sea (East of Shetlands). They were carried out under two conditions: static and dynamic.
They were designed previous to departure but the procedures inevitably had to be adapted to the conditions (especially space and time) and equipment available on the rig.
The following equipment was transported on board (via helicopter with the author):
- sieves (these sieves are the same ones as the one used previously for the sieving experiments in the School laboratories:

- 9.500 mm
- 4.000 mm
- 3.350 mm
- 2.000 mm
- mm
- 0.090 mm

The first five sieves were used to determine the cuttings size ranges before conducting the test for disaggregation, while the last one was supposed to be used to check the size of fine particles after disaggregation.
- 2 chronometers (digital handhold stopwatches). They were RS components with a precision of 1/100sec;
- one thermometer (mercury type). It is graduated from -10^{0}C to +110^{0}C every 1^{0}C, and;
- 6 glass beakers (Pyrex). They all had the same volume (250 ml) and were graduated till 200 ml.
The rest of the equipment (bucket, spoons, sink...etc) was borrowed on board.

Procedures

The following procedures were valid for the experiments under static conditions.

1. Three plastic cups of wet cuttings were taken directly from the shakers just before the discharge chute. They were then mixed in a glass dish.
2. The time of sampling was recorded.
3. The temperature of the wastes (mud and cuttings) was measured at different points in the cuttings flowmeter, the shakers end of screens and the mud flow at the exit of the shakers. The cuttings flowmeter is an apparatus placed just between the shakers and the discharge chute to measure the amount of cuttings discharged during operations.
4. The cuttings were then sieved using the carried sieves and tap water from the mud logging unit.
5. A bucket was filled with filtered seawater and its temperature was measured at the tap (T_1 SW).

6. The density was read for the sample from measurements provided by the mud loggers (see density measurements procedures).
7. 200 ml of seawater was poured into two beakers. A white sheet of paper was placed under the beakers so the changes in appearance or shape of the cuttings would be easier to notice.
8. The temperature of the seawater was measured into the beakers several time during the experiments (T_2 SW)
9. One cutting was placed in a beaker and the stop watch was started.
10. Any change in the appareance or the shape of the cutting was then checked and the time was stopped.

For experiments carried out under dynamic conditions, steps 1 to 6 (inclusive) were similar and the following steps were then carried out:

7. A plastic bottle was filled in with filtered seawater.
8. The temperature of the seawater was checked just before the start of the experiment.
9. One cutting was placed in the bottle.
10. The bottle was then handled in the horizontal position and rocked with a regular frequency and amplitude 30 times.
11. The cutting was then checked for change in appearance or shape.

The reason why this method has been adopted is because no mecanic shaker was available. There was a magnetic agitator on board but the mudman was using it regularly to conduct tests on the drilling muds. Plus, when using such a device, it is needed to place a magnet inside the beaker to create the agitation. The magnet would have then been in contact with the cutting in the beaker and would have changed the conditions of the experiments completely. The method used seemed quite coarse and not extremely scientific but it was thought to be the best option to create a similar turbulence as in the surface layer of the sea. Of course, conclusions after such experiments cannot be of true scientific value but will give some indication about the disaggregation of the cuttings.

Results and conclusion

The following table summarises the conditions and results for the experiments.

No	Condition	Shape	Range size	Time sampling	To cut	To SW	T2 SW	density	Tdis	Changes	% 90 um
1	S	A	9.5/4.0	16.45	50	11	13	2.07	5' +	None	N/A
2	S	A	9.5/4.0	16.45	50	11	13	2.07	5' +	None	N/A
3	S	F	9.5/4.0	16.45	50	11	13	2.07	5' +	None	N/A
4	S	F	9.5/4.0	16.45	50	11	13	2.07	5' +	None	N/A
5	S	R	9.5/4.0	16.45	50	11	13	2.07	5' +	Primary	N/A
6	S	R	9.5/4.0	16.45	50	11	13	2.07	5' +	Primary	N/A

7	S	A	4.0/3.35	16.45	50	11	14	2.07	5' +	Primary	N/A
8	S	A	4.0/3.35	16.45	50	11	14	2.07	5' +	Primary	N/A
9	S	F	4.0/3.35	16.45	50	11	14	2.07	5' +	None	N/A
10	S	F	4.0/3.35	16.45	50	11	14	2.07	5' +	None	N/A
11	S	A	3.35/2.0	16.45	50	11	14	2.07	5' +	None	N/A
12	S	A	3.35/2.0	16.45	50	11	14	2.07	5' +	None	N/A
13	S	F	3.35/2.0	16.45	50	11	14	2.07	5' +	None	N/A
14	S	F	3.35/2.0	16.45	50	11	14	2.07	5' +	None	N/A
15	S	A	2.0/1.0	16.45	50	11	14	2.07	5' +	None	N/A
16	S	A	2.0/1.0	16.45	50	11	14	2.07	5' +	None	N/A
17	S	F	2.0/1.0	16.45	50	11	14	2.07	5' +	None	N/A
18	S	F	2.0/1.0	16.45	50	11	14	2.07	5' +	None	N/A
19	D	A	9.5/4.0	8.15	50	11	16	2.05	30s+	Primary	N/A
20	D	A	9.5/4.0	8.15	50	11	16	2.05	30s+	Primary	N/A
21	D	A	9.5/4.0	8.15	50	11	16	2.05	30s+	None	N/A
22	D	F	9.5/4.0	8.15	50	11	16	2.05	30s+	None	N/A
23	D	F	9.5/4.0	8.15	50	11	16	2.05	30s+	None	N/A
24	D	F	9.5/4.0	8.15	50	11	16	2.05	30s+	None	N/A
25	D	F	4.0/3.35	8.15	50	11	16	2.05	30s+	None	N/A
26	D	F	4.0/3.35	8.15	50	11	16	2.05	30s+	None	N/A
27	D	F	4.0/3.35	8.15	50	11	16	2.05	30s+	None	N/A
28	D	F	3.35/2.0	8.15	50	11	16	2.05	30s+	None	N/A
29	D	F	3.35/2.0	8.15	50	11	16	2.05	30s+	None	N/A
30	D	F	3.35/2.0	8.15	50	11	16	2.05	30s+	None	N/A
31	D	F	2.0/1.0	8.15	50	11	16	2.05	30s+	None	N/A
32	D	F	2.0/1.0	8.15	50	11	16	2.05	30s+	None	N/A
33	D	F	2.0/1.0	8.15	50	11	16	2.05	30s+	None	N/A

Table.1: Results from the disaggregation tests.

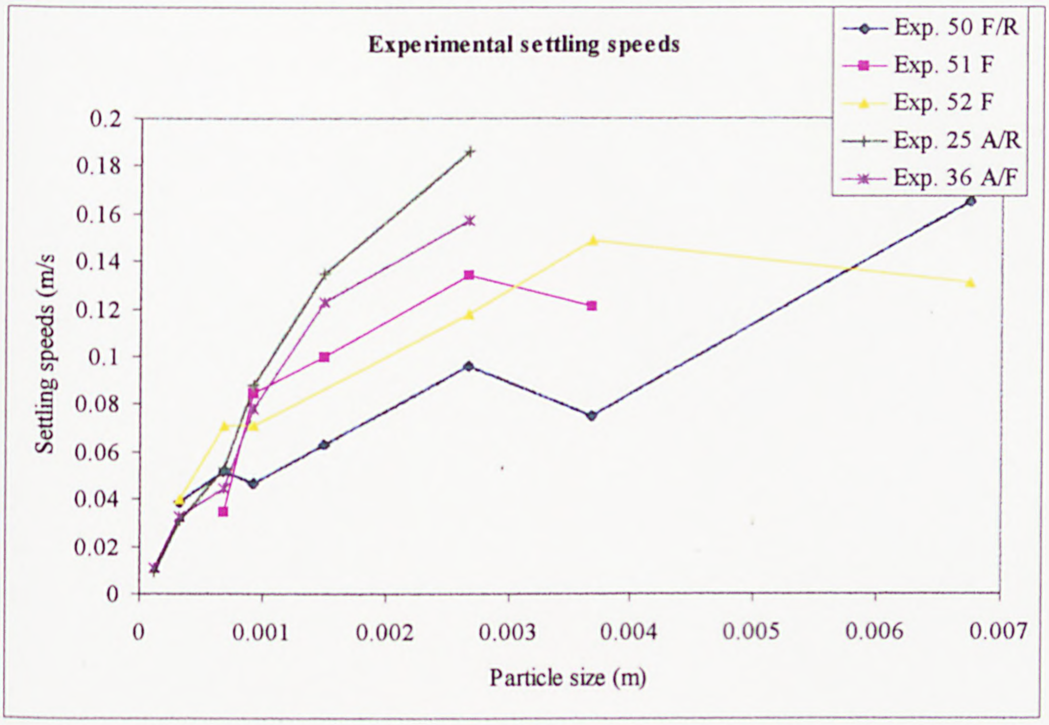
The different parameters included in this table are as follows:
- No: this is the number of the experiment;
- Condit.: is the condition (static - S- or dynamic - D) of the experiment;

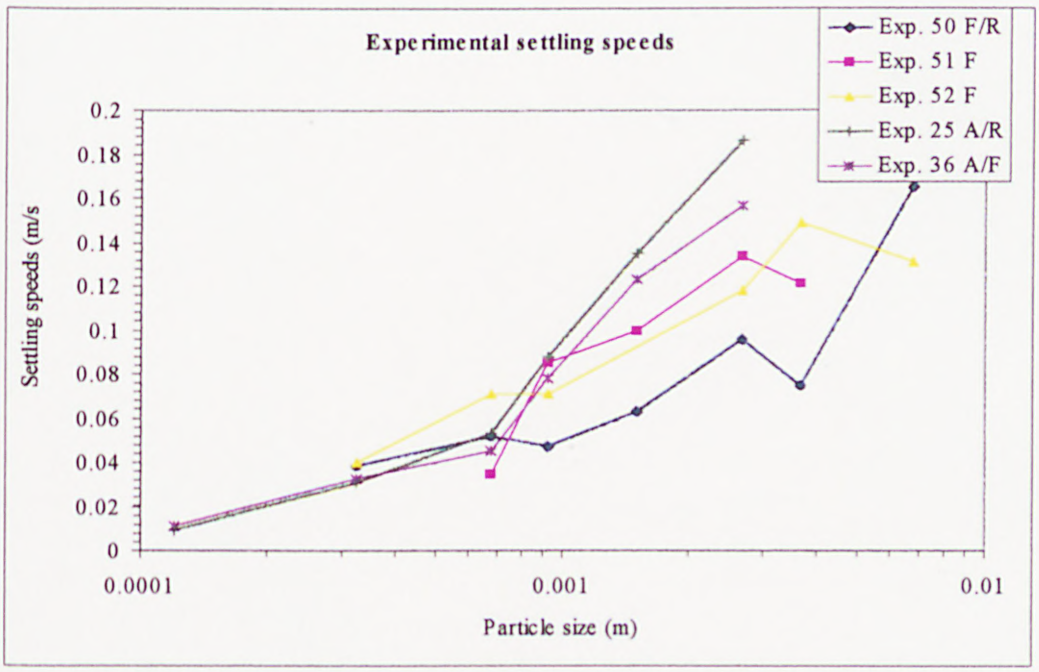
- Shape: is the shape of the particle and is coded using the same abbreviations as for laboratory sieving experiments (i.e. A: angular, F: flat and R: round);
- Range size: corresponds to the upper and lower sieves (e.g. 4.0/3.35 means that the particle was caught between the 4.0 mm and 3.35 mm sieves);
- Time sampling: is the real time at which the sample of cuttings was taken directly from the shale shakers (a substantial sample of cuttings was taken at once in order not to have to repeat the sampling again);
- To cut: is the temperature (in degrees Celsius) of the cuttings and mud that was measured at the exit of the shale shakers just before the discharge chute. Some comments are made about the temperature measurements points later on in this section;
- To SW: is the temperature (in degrees Celsius) of the seawater measured at the tap;
- T2 SW: is the temperature (in degrees Celsius) of the seawater measured in the beaker (for the static condition) or in the plastic bottle (for the dynamic condition);
- Density: is the density (sg) of the dry cuttings measured by the mudlogger at regular intervals (for the static conditions the values were taken from measurements made at 16.15 and for dynamic conditions, at 8.10am);
- Tdis: is the time of complete disaggregation (only visually assessed) of the cuttings in seawater under the conditions of the experiments;
- Changes: represents the changes in the appearance or the shape of the cuttings after visual assessment. 'None' means that there was no changes in the apparent shape of the cutting and 'Primary' means that after a short time (less than 3 mins), the first 'coating' of the cutting surface was apparently changed. After this primary change, there was no further apparent modifications of the cutting.

During an experiment with one cutting (static or dynamic), the following parameters are constant:
- the temperature of the seawater;
- the volume of seawater;
- the number of particle, and;
- the condition of the medium (static or dynamic).

There are different types of clays: they can vary in colour, friability, hardness ...etc. At the time of the offshore experiments, the drilled clay formation was relatively deep and therefore, the clay was hard. It was still friable but the disaggregation properties were different than a soft clay from higher formation. A clay is not always harder with depth, it also depends on the presence of a layer of different lithology that would 'protect' the following layer of clay.
In order to study this problem in further details, the different types of clays should be investigated (see section 6.3.1) as well as their respective properties (densities, hardness, friability ...etc). According to the mudloggers met on the rig, swelling clays from upper formations will quickly absorb water (or any liquid) and disaggregate rapidly.

APPENDIX.4: SETTLING SPEED DISTRIBUTIONS.


Experimental settling speeds
Exp. 50 F/R
Exp. 51 F
Exp. 52 F
Exp. 25 A/R
Exp. 36 A/F
Settling speeds (m/s)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
Particle size (m)


Experimental settling speeds
Exp. 50 F/R
Exp. 51 F
Exp. 52 F
Exp. 25 A/R
Exp. 36 A/F
Settling speeds (m/s)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.0001
0.001
0.01
Particle size (m)

APPENDIX.5: FORTRAN 90 SUBROUTINES USED FOR THE MODEL.

CD1 : FOR ANGULAR PARTICLES.

```
XCOMP = UG+UGF-U(1)
YCOMP = VG+VGF-U(2)
ZCOMP = WG+WGF-U(3)

VREL = SQRT(XCOMP*XCOMP+YCOMP*YCOMP+ZCOMP*ZCOMP)

REYN = DENGAS*D*VREL/VISGAS

TINY = 1.0D-17

CD = (4.D0*D*(2.39D0*10.D0**3.D0-1000.D0)*9.81D0*0.7D0)
+                    /(3.D0*1000.D0*(VREL**2.D0))
```

CD2 : FOR ROUND PARTICLES WITH RUBEY.

```
XCOMP = UG+UGF-U(1)
YCOMP = VG+VGF-U(2)
ZCOMP = WG+WGF-U(3)

VREL = SQRT(XCOMP*XCOMP+YCOMP*YCOMP+ZCOMP*ZCOMP)

REYN = DENGAS*D*VREL/VISGAS

TINY = 1.0D-17

CD = (24.D0/MAX(REYN,TINY))+2.D0
```

CD3 : FOR ROUND PARTICLES WITH DALLAVALLE.

```
XCOMP = UG+UGF-U(1)
YCOMP = VG+VGF-U(2)
ZCOMP = WG+WGF-U(3)

VREL = SQRT(XCOMP*XCOMP+YCOMP*YCOMP+ZCOMP*ZCOMP)

REYN = DENGAS*D*VREL/VISGAS

TINY = 1.0D-17

CD = (24.4D0/MAX(REYN,TINY))+0.4D0
```

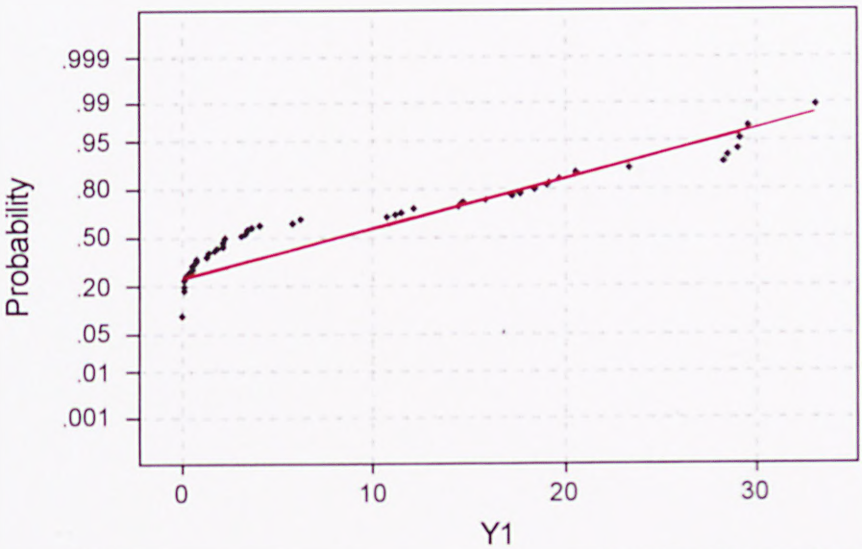
```
---------------------------------------------------------------

CD7 : FOR DISKS WITH REYN>133.
---------------------------------

    XCOMP = UG+UGF-U(1)
    YCOMP = VG+VGF-U(2)
    ZCOMP = WG+WGF-U(3)

    VREL = SQRT(XCOMP*XCOMP+YCOMP*YCOMP+ZCOMP*ZCOMP)

    REYN = DENGAS*D*VREL/VISGAS

    TINY = 1.0D-17

    CD = 1.17D0


---------------------------------------------------------------

CD9 : FOR THE LONG CYLINDERS WITH 5<REYN<40.
-------------------------------------------

    XCOMP = UG+UGF-U(1)
    YCOMP = VG+VGF-U(2)
    ZCOMP = WG+WGF-U(3)

    VREL = SQRT(XCOMP*XCOMP+YCOMP*YCOMP+ZCOMP*ZCOMP)

    REYN = DENGAS*D*VREL/VISGAS

    TINY = 1.0D-17

    CD = (9.689D0*REYN**(-0.78D0))*(1.D0+0.227D0*REYN**0.55D0)


---------------------------------------------------------------

CD10 : FOR LONG CYLINDERS WITH 40<REYN<400.
---------------------------------------------

    XCOMP = UG+UGF-U(1)
    YCOMP = VG+VGF-U(2)
    ZCOMP = WG+WGF-U(3)

    VREL = SQRT(XCOMP*XCOMP+YCOMP*YCOMP+ZCOMP*ZCOMP)

    REYN = DENGAS*D*VREL/VISGAS

    TINY = 1.0D-17

    CD = (9.689D0*REYN**(-0.78D0))*(1.D0+0.0838D0*REYN**0.82D0)
```

APPENDIX.6: TABLE WITH ALL RESULTS.

Particle	Size	Shape	Rep (exp)	Cd	Cd1	Cd2	Cd3	Vexp	Vth	Vth1	Vth2	Vth3	Vcfd	V1	V2	V3
(No)	(m)	(n/a)	(n/a)	(No)	(n/a)	(n/a)	(n/a)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
1	0.009525	1	4555	2,3	2.005	0.405	0.431	0.548	0.586	0.275	0.611	0.593	0.587	0.274	0.611	0.593
2	0.003175	1	839	2,3	2.029	0.429	0.454	0.303	0.345	0.161	0.350	0.340	0.342	0.160	0.351	0.341
3	0.00675	0.5	772	1,7	3.581	1.170	4.151	0.131	0.529	0.185	0.324	0.172	0.529	0.185	0.324	0.172
4	0.00675	0.4	972	1,10	1.806	1.114	6.512	0.165	0.529	0.197	0.332	0.137	0.529	0.261	0.331	0.271
5	0.003675	0.4	241	1,10	4.758	1.146	6.587	0.075	0.390	0.090	0.242	0.101	0.390	0.119	0.245	0.198
6	0.003675	0.5	388	1,7	2.285	1.170	4.182	0.121	0.390	0.171	0.239	0.126	0.390	0.171	0.239	0.127
7	0.003675	0.5	478	1,7	1.507	1.170	4.170	0.149	0.390	0.211	0.239	0.127	0.390	0.211	0.239	0.127
8	0.002675	0.4	224	1,10	2.114	1.150	6.595	0.096	0.333	0.115	0.206	0.086	0.315	0.152	0.209	0.168
9	0.002675	0.5	313	1,7	1.356	1.170	4.197	0.134	0.333	0.190	0.204	0.108	0.315	0.190	0.204	0.108
10	0.002675	0.5	275	1,7	1.749	1.170	4.207	0.118	0.333	0.167	0.204	0.108	0.315	0.167	0.204	0.108
11	0.002675	0.8	434	1,7	1.126	1.170	1.111	0.186	0.333	0.208	0.204	0.209	0.315	0.208	0.204	0.210
12	0.002675	0.6	366	1,10	1.186	1.125	2.682	0.157	0.333	0.203	0.208	0.135	0.315	0.203	0.209	0.135
13	0.0015	0.4	82	1,10	2.753	1.279	6.779	0.063	0.249	0.075	0.146	0.063	0.193	0.100	0.154	0.064
14	0.0015	0.5	131	1,10	1.366	1.203	4.303	0.100	0.249	0.141	0.151	0.080	0.193	0.141	0.154	0.079
15	0.0015	0.8	177	1,3	1.199	0.538	1.191	0.135	0.249	0.151	0.225	0.151	0.193	0.151	0.239	0.152
16	0.0015	0.6	161	1,10	1.083	1.179	2.766	0.123	0.249	0.159	0.152	0.099	0.193	0.159	0.154	0.099
17	0.000925	0.4	38	1,9	3.050	1.521	7.120	0.047	0.196	0.056	0.105	0.049	0.130	0.074	0.128	0.092
18	0.000925	0.5	69	1,10	1.166	1.320	4.470	0.085	0.196	0.120	0.113	0.061	0.130	0.120	0.116	0.060
19	0.000925	0.5	57	1,10	1.671	1.367	4.539	0.071	0.196	0.100	0.111	0.061	0.130	0.100	0.116	0.060
20	0.000925	0.8	71	1,3	1.740	0.744	1.393	0.088	0.196	0.098	0.151	0.110	0.130	0.098	0.170	0.113
21	0.000925	0.6	63	1,10	1.661	1.341	2.998	0.078	0.196	0.101	0.112	0.075	0.130	0.100	0.116	0.075
22	0.000675	0.9	31	2,3	2.784	1.197	1.454	0.052	0.167	0.066	0.101	0.092	0.091	0.069	0.131	0.100
23	0.000675	0.9	21	2,3	3.164	1.584	1.834	0.035	0.167	0.062	0.088	0.082	0.091	0.069	0.131	0.100
24	0.000675	0.9	42	2,3	2.574	0.983	1.244	0.071	0.167	0.069	0.112	0.099	0.091	0.069	0.131	0.100
25	0.000675	0.9	31	2,3	2.769	1.182	1.439	0.053	0.167	0.067	0.102	0.092	0.091	0.069	0.131	0.100
26	0.000675	0.9	27	2,3	2.905	1.321	1.576	0.045	0.167	0.065	0.096	0.088	0.091	0.069	0.131	0.100
27	0.000325	0.9	11	2,3	4.170	2.606	2.840	0.039	0.116	0.038	0.048	0.046	0.039	0.037	0.054	0.050
28	0.000325	0.9	11	2,3	4.116	2.551	2.786	0.040	0.116	0.038	0.048	0.046	0.039	0.037	0.054	0.050
29	0.000325	0.9	9	2,3	4.730	3.175	3.400	0.031	0.116	0.035	0.043	0.042	0.039	0.037	0.054	0.050
30	0.000325	0.9	9	2,3	4.564	3.007	3.235	0.033	0.116	0.036	0.044	0.043	0.039	0.037	0.054	0.050
31	0.00012	0.9	1	2,3	27.46	26.29	26.13	0.009	0.070	0.009	0.009	0.009	0.008	0.009	0.009	0.009
32	0.00012	0.9	1	2,3	22.83	21.58	21.50	0.011	0.070	0.010	0.010	0.010	0.008	0.009	0.009	0.009

APPENDIX.7: NORMALITY TESTS.

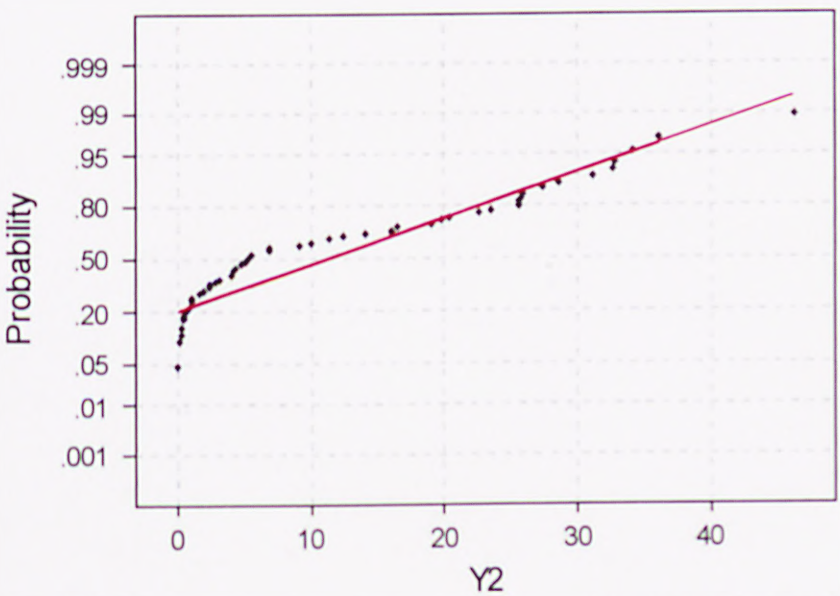
Normality test for y1



Average: 8.27265
StDev: 10.1465
N: 57

Anderson-Darling Normality Test
A-Squared: 4.822
P-Value: 0.000

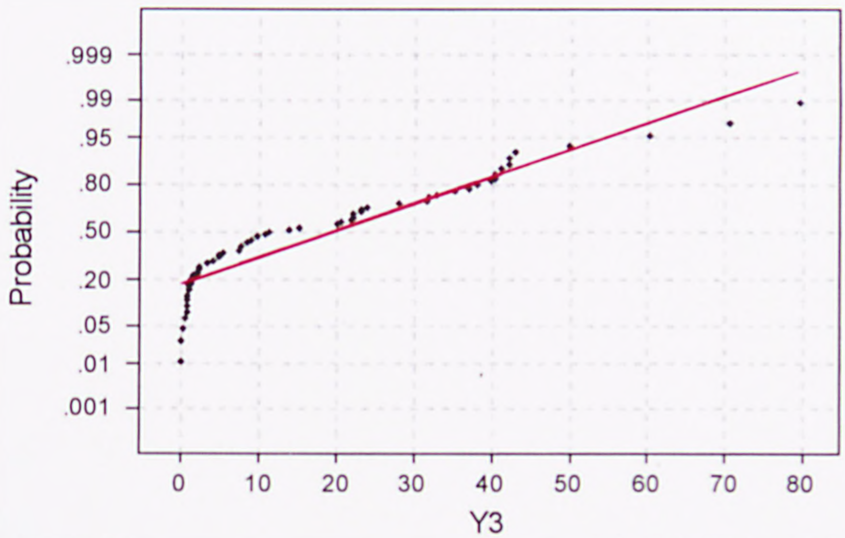
Normality test for y2



Average: 11.2980
StDev: 12.2856
N: 57

Anderson-Darling Normality Test
A-Squared: 3.534
P-Value: 0.000

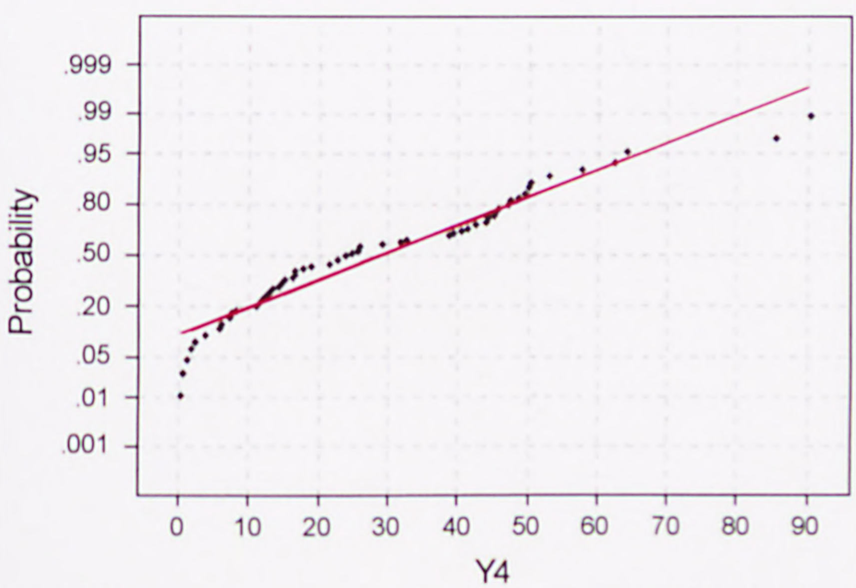
Normality test for y3



Average: 19.2920
StDev: 19.4381
N: 57

Anderson-Darling Normality Test
A-Squared: 2.349
P-Value: 0.000

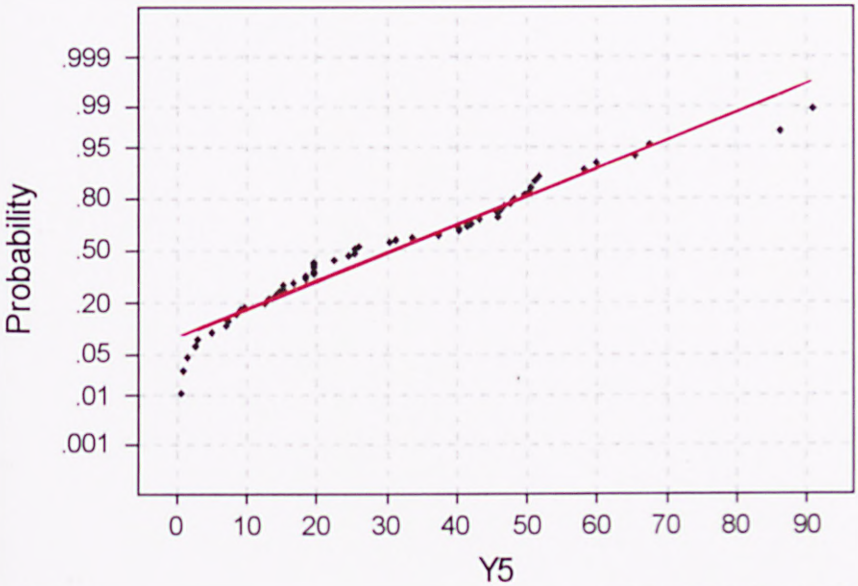
Normality test for y4



Average: 28.8357
StDev: 21.1540
N: 57

Anderson-Darling Normality Test
A-Squared: 1.120
P-Value: 0.006

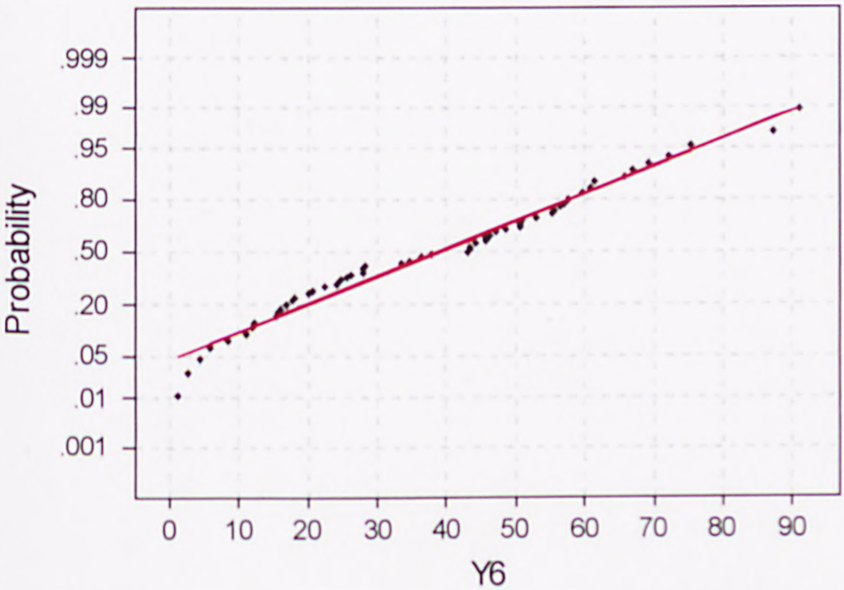
Normality test for y5



Average: 30.5965
StDev: 21.2785
N: 57

Anderson-Darling Normality Test
A-Squared: 0.929
P-Value: 0.017

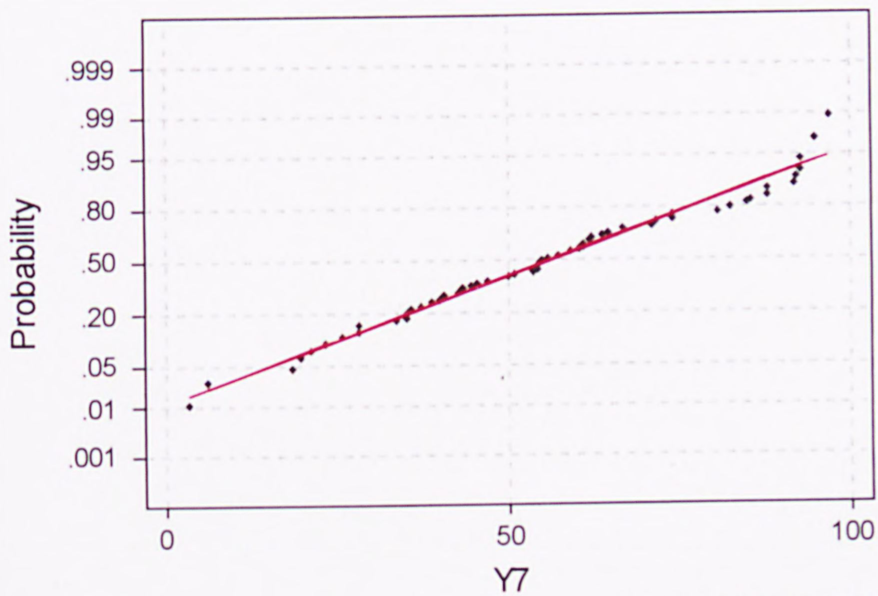
Normality test for y6



Average: 38.7795
StDev: 22.1647
N: 57

Anderson-Darling Normality Test
A-Squared: 0.523
P-Value: 0.176

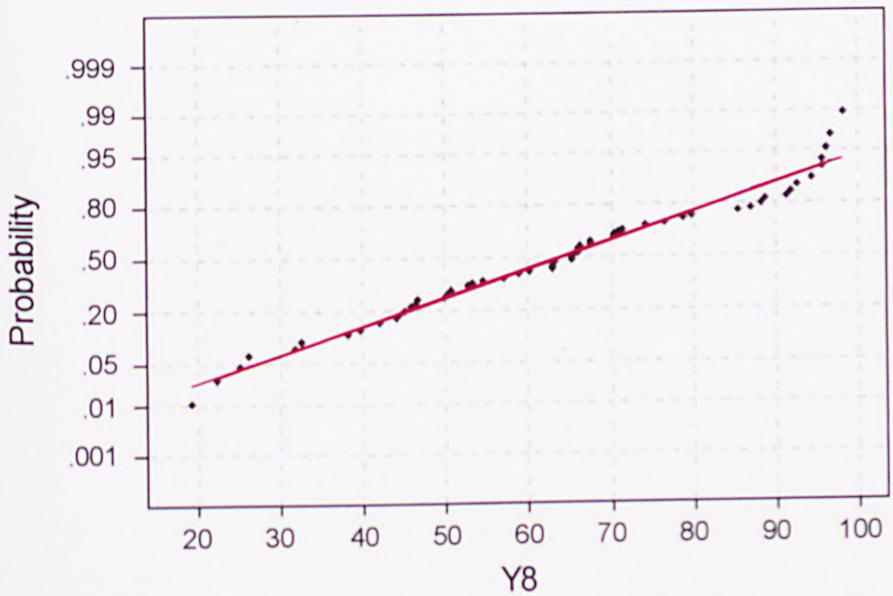
Normality test for y7



Average: 55.9263
StDev: 24.1757
N: 57

Anderson-Darling Normality Test
A-Squared: 0.382
P-Value: 0.387

Normality test for y8



Average: 63.9277
StDev: 21.5487
N: 57

Anderson-Darling Normality Test
A-Squared: 0.508
P-Value: 0.191

APPENDIX.8: RESULTS FROM THE FINAL REGRESSION MODEL AND RESIDUALS PLOTS FOR EACH SAMPLE.

Regression Analysis

The regression equation is
Y1 = 0.87 + 14.0 Quaterna + 8.57 Too-20 + 0.00947 Dep-Cret - 23.6 WBM-Cret
+ 7.68 Ins-20 -0.000283 Dep-Sect + 0.00273 Dep-WBM + 0.00440 Dep-
40

Predictor	Coef	StDev	T	P
Constant	0.874	2.772	0.32	0.754
Quaterna	13.998	2.861	4.89	0.000
Too-20	8.570	2.262	3.79	0.000
Dep-Cret	0.009468	0.001455	6.51	0.000
WBM-Cret	-23.574	4.365	-5.40	0.000
Ins-20	7.681	2.628	2.92	0.006
Dep-Sect	-0.0002834	0.0001197	-2.37	0.023
Dep-WBM	0.0027314	0.0008823	3.10	0.004
Dep-40	0.0044031	0.0009251	4.76	0.000

S = 5.016 R-Sq = 72.2% R-Sq(adj) = 66.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	8	2678.26	334.78	13.31	0.000
Residual Error	41	1031.50	25.16		
Total	49	3709.76			

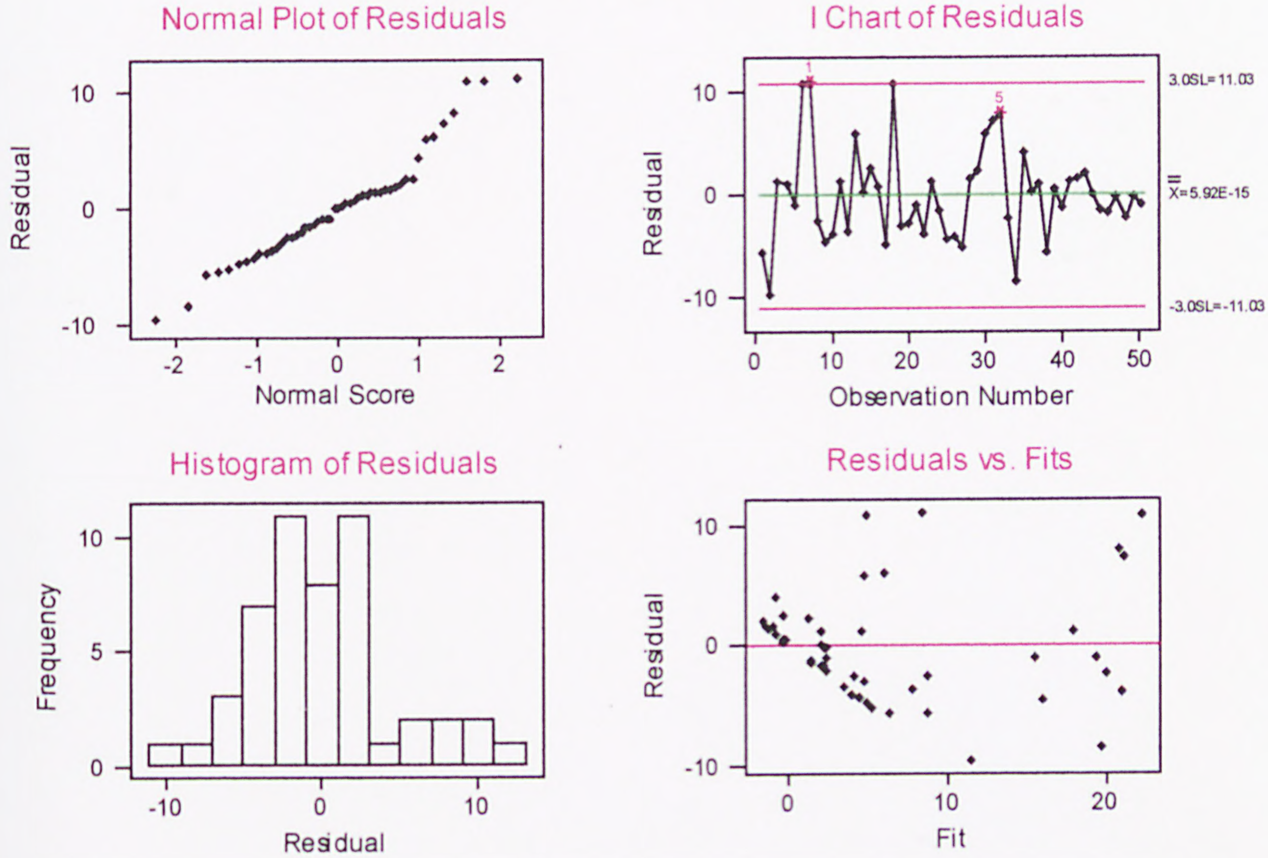
Source	DF	Seq SS
Quaterna	1	999.84
Too-20	1	12.44
Dep-Cret	1	713.96
WBM-Cret	1	340.75
Ins-20	1	5.80
Dep-Sect	1	0.03
Dep-WBM	1	35.46
Dep-40	1	569.97

Unusual Observations

Obs	Quaterna	Y1	Fit	StDev Fit	Residual	St Resid
2	0.00	1.747	11.440	1.898	-9.693	-2.09R
6	0.00	33.073	22.207	2.706	10.866	2.57R
7	0.00	19.733	8.519	1.979	11.214	2.43R
18	0.00	15.847	4.849	2.131	10.998	2.42R
22	0.00	17.193	21.022	3.752	-3.829	-1.15 X

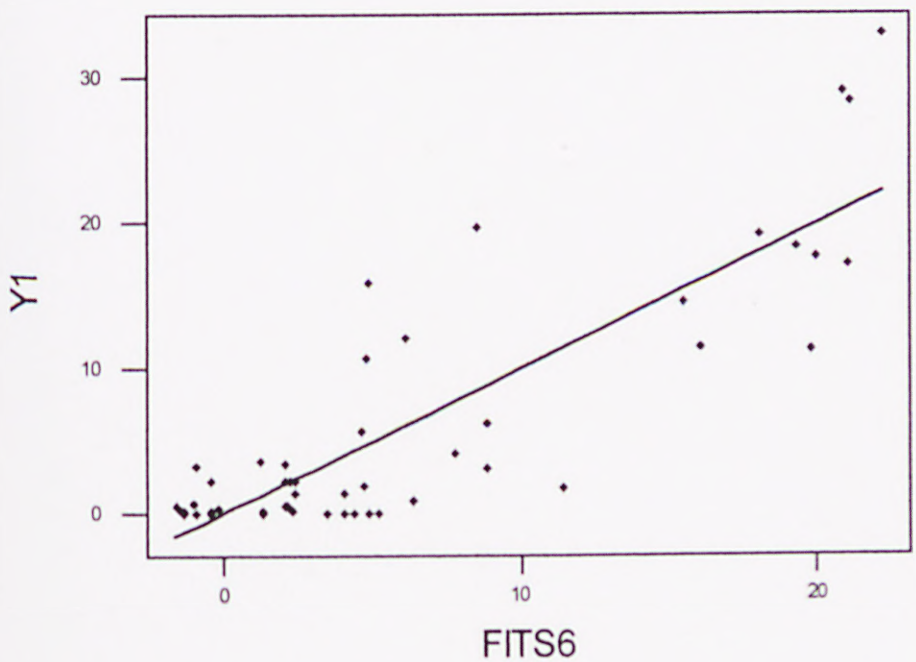
R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

Residual plots for Y1



Fitted line for y1

Y = 1.51E-14 + 1X
R-Sq = 72.2 %



Regression Analysis

The regression equation is

Y2 = 19.8 - 12.1 Sect-Ins - 22.6 Ins-40 + 20.3 Jur-20 + 0.0113 Dep-WBM
+ 284 Insert - 55.4 WBM + 67.8 Tooth + 0.0443 Sect^2 - 24.6 20/40
- 31.4 >100 - 0.0349 Dep-Ins - 0.0270 Dep-Too - 0.0318 Dep-Olig
- 0.00791 Dep-Jur + 0.0124 Dep-40

Predictor	Coef	StDev	T	P
Constant	19.849	3.614	5.49	0.000
Sect-Ins	-12.135	1.290	-9.41	0.000
Ins-40	-22.608	6.054	-3.73	0.001
Jur-20	20.254	6.670	3.04	0.005
Dep-WBM	0.011327	0.002679	4.23	0.000
Insert	283.53	29.67	9.56	0.000
WBM	-55.440	8.444	-6.57	0.000
Tooth	67.816	8.886	7.63	0.000
Sect^2	0.04429	0.01548	2.86	0.007
20/40	-24.623	5.296	-4.65	0.000
>100	-31.413	5.314	-5.91	0.000
Dep-Ins	-0.034899	0.004740	-7.36	0.000
Dep-Too	-0.027021	0.003449	-7.84	0.000
Dep-Olig	-0.031757	0.003607	-8.80	0.000
Dep-Jur	-0.007908	0.001861	-4.25	0.000
Dep-40	0.012409	0.002420	5.13	0.000

S = 4.349 R-Sq = 88.1% R-Sq(adj) = 82.9%

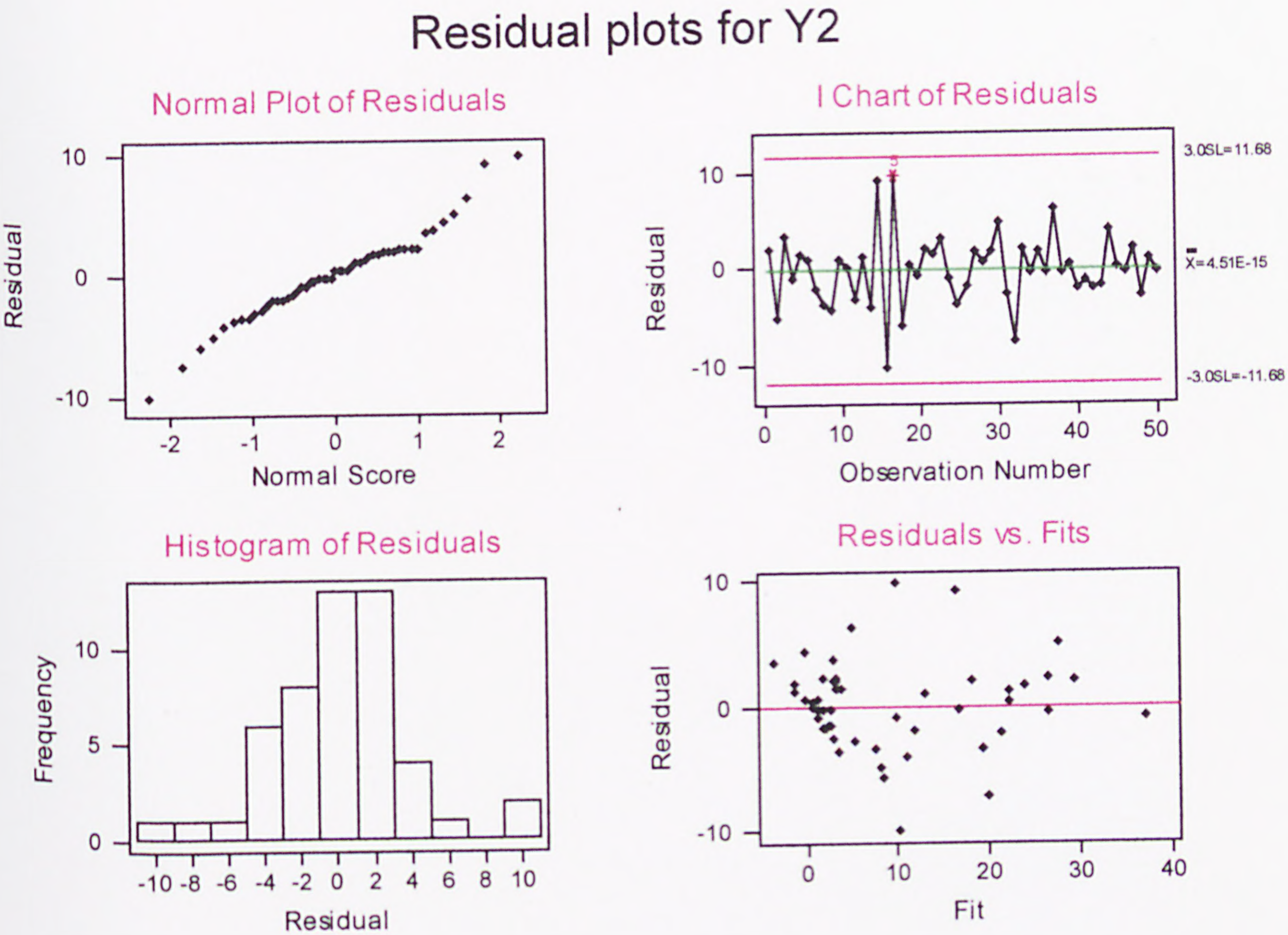
Analysis of Variance

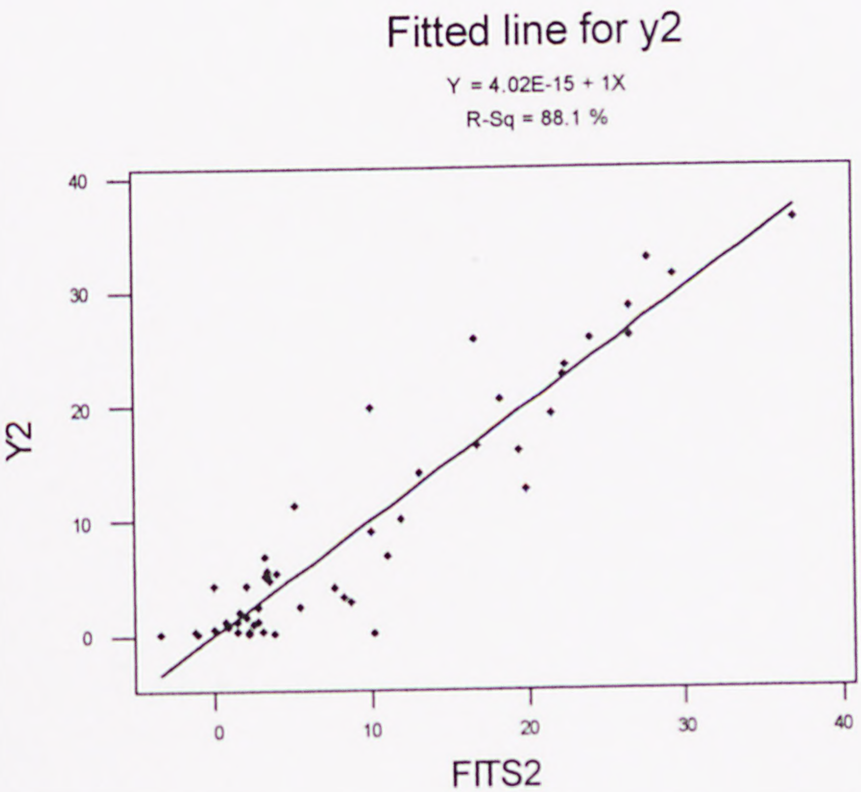
Source	DF	SS	MS	F	P
Regression	15	4783.12	318.87	16.86	0.000
Residual Error	34	643.06	18.91		
Total	49	5426.18			

Source	DF	Seq SS
Sect-Ins	1	2.37
Ins-40	1	15.30
Jur-20	1	702.93
Dep-WBM	1	5.55
Insert	1	307.34
WBM	1	85.92
Tooth	1	6.83
Sect^2	1	539.22
20/40	1	0.10
>100	1	86.23
Dep-Ins	1	264.97
Dep-Too	1	122.67
Dep-Olig	1	1747.78
Dep-Jur	1	398.60
Dep-40	1	497.30

Unusual Observations

Obs	Sect-Ins	Y2	Fit	StDev Fit	Residual	St Resid
15	17.5	25.760	16.615	2.120	9.145	2.41R
16	17.5	0.000	10.132	1.566	-10.132	-2.50R
17	17.5	19.753	9.944	1.560	9.809	2.42R
50	8.5	2.427	2.807	4.278	-0.380	-0.48 X

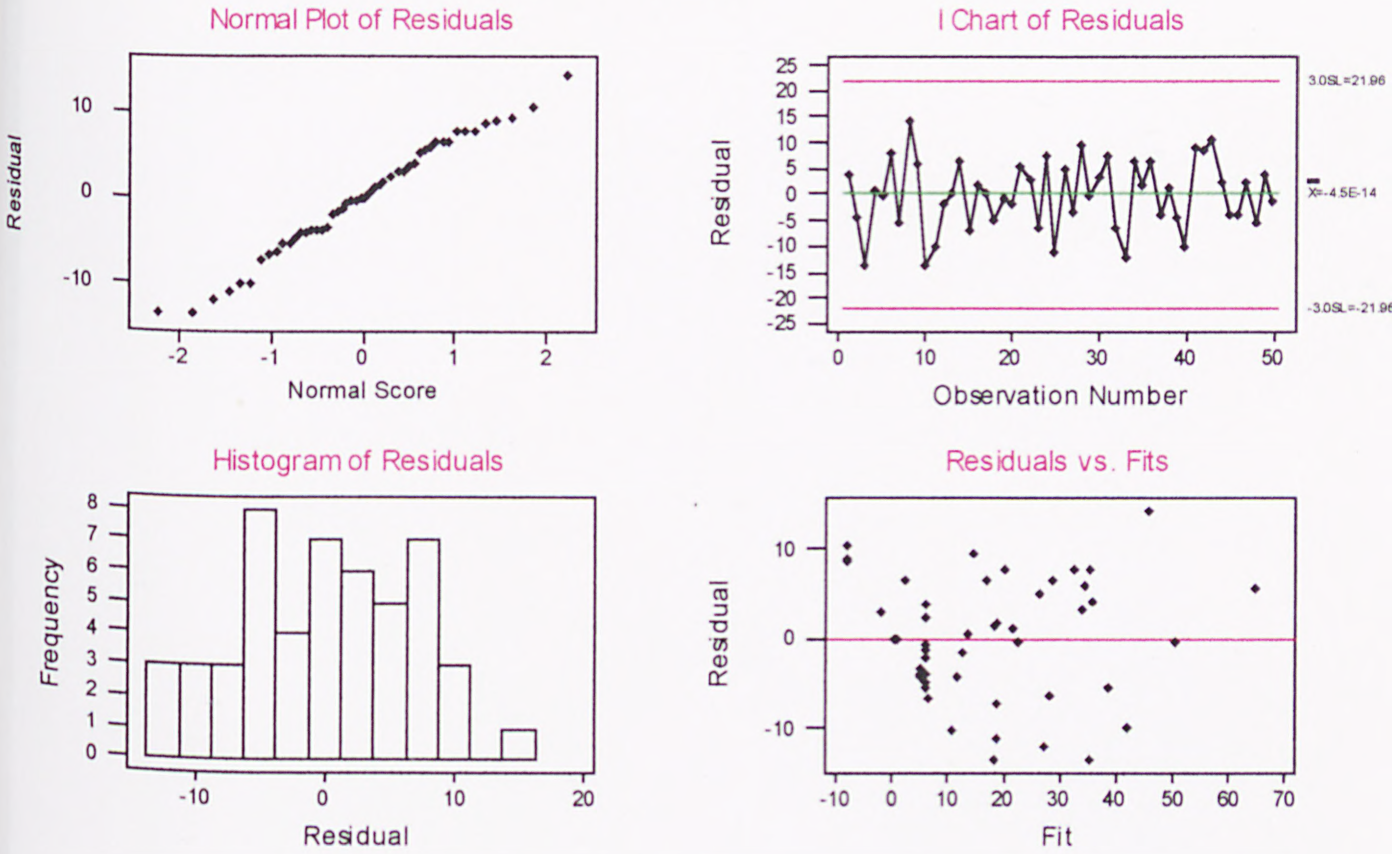

Residual plots for Y2
Normal Plot of Residuals
Residual
Normal Score
I Chart of Residuals
3.0SL=11.68
X=4.51E-15
-3.0SL=-11.68
Observation Number
Histogram of Residuals
Frequency
Residual
Residuals vs. Fits
Fit


Fitted line for y2
Y = 4.02E-15 + 1X
R-Sq = 88.1 %
Y2
FITS2

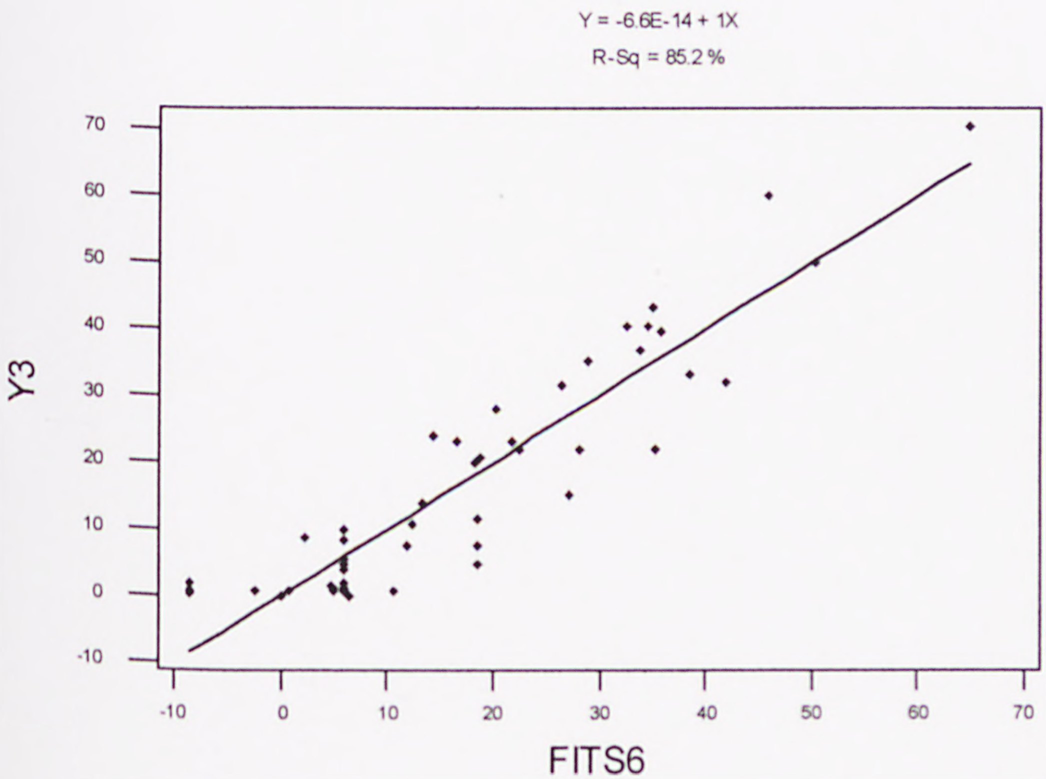
Regression Analysis
Regression Analysis

```
The regression equation is
Y3 = 75.6 - 3.87 Section - 36.7 WBM - 59.6 Cretaceo + 4.24 Sect-Too
          + 0.0287 Dep-Cret - 0.0341 Dep-Olig - 0.0110 Dep-Too
          + 0.00463 Dep-40 + 0.0692 Dep-100 - 0.0439 Dep->100 + 34.8 Ins-20

Predictor         Coef       StDev          T        P
Constant         75.64       12.04       6.28    0.000
Section        -3.8711      0.7601      -5.09    0.000
WBM            -36.710       5.873      -6.25    0.000
Cretaceo       -59.596       9.648      -6.18    0.000
Sect-Too        4.2371      0.5286       8.02    0.000
Dep-Cret      0.028661    0.003487       8.22    0.000
Dep-Olig     -0.034064    0.006516      -5.23    0.000
Dep-Too      -0.011021    0.003743      -2.94    0.005
Dep-40        0.004629    0.001385       3.34    0.002
Dep-100        0.06924     0.01317       5.26    0.000
Dep->100      -0.04391     0.01401      -3.13    0.003
Ins-20          34.769       6.047       5.75    0.000

S = 7.594       R-Sq = 85.2%     R-Sq(adj) = 81.0%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression        11     12650.9      1150.1     19.95    0.000
Residual Error    38      2191.1        57.7
Total             49     14842.1

Source        DF      Seq SS
Section        1         1.2
WBM            1       936.9
Cretaceo       1      1988.7
Sect-Too       1      1974.0
Dep-Cret       1      2969.5
Dep-Olig       1      1371.2
Dep-Too        1        17.7
Dep-40         1        86.8
Dep-100        1       403.5
Dep->100       1       994.9
Ins-20         1      1906.5

Unusual Observations
Obs    Section         Y3         Fit   StDev Fit    Residual    St Resid
  8       12.3      60.19       45.77        4.08       14.42       2.25R
 10       12.3      21.90       35.41        4.00      -13.51      -2.09R
 17       17.5       0.03        0.03        7.59       -0.00         * X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.
```

Residual plots for Y3



Fitted line for y3



Regression Analysis

The regression equation is
Y4 = 147 - 247 WBM - 76.2 Cretaceo - 67.6 >100 + 7.99 Sect-Mud + 26.0 WBM-Too + 22.5 Too-Pale + 42.0 Jur-20 - 0.00306 Dep-Sect - 0.0415 Dep-Olig + 0.0429 Dep-Cret + 0.0282 Dep-WBM + 0.0107 Dep-Ins + 0.00490 Dep-40

Predictor	Coef	StDev	T	P
Constant	147.23	17.21	8.55	0.000
WBM	-247.37	35.03	-7.06	0.000
Cretaceo	-76.16	11.58	-6.58	0.000
>100	-67.567	9.499	-7.11	0.000
Sect-Mud	7.988	1.350	5.92	0.000
WBM-Too	26.035	5.199	5.01	0.000
Too-Pale	22.523	6.881	3.27	0.002
Jur-20	41.974	9.344	4.49	0.000
Dep-Sect	-0.0030556	0.0004772	-6.40	0.000
Dep-Olig	-0.041510	0.007217	-5.75	0.000
Dep-Cret	0.042876	0.005243	8.18	0.000
Dep-WBM	0.028228	0.005941	4.75	0.000
Dep-Ins	0.010735	0.002228	4.82	0.000
Dep-40	0.004902	0.001541	3.18	0.003

S = 8.444   R-Sq = 88.2%   R-Sq(adj) = 84.0%

Analysis of Variance

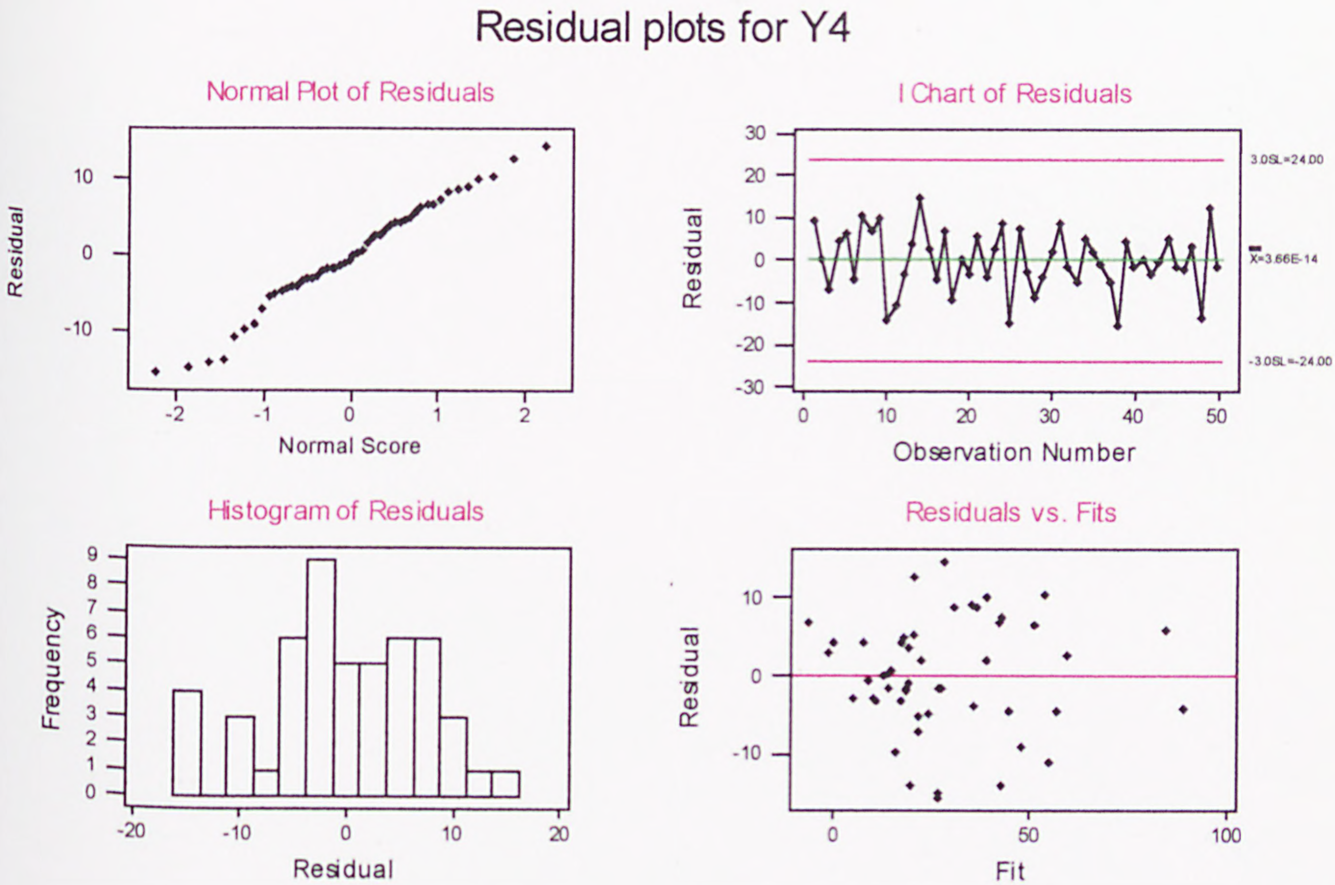
Source	DF	SS	MS	F	P
Regression	13	19226.9	1479.0	20.74	0.000
Residual Error	36	2567.0	71.3		
Total	49	21793.9			

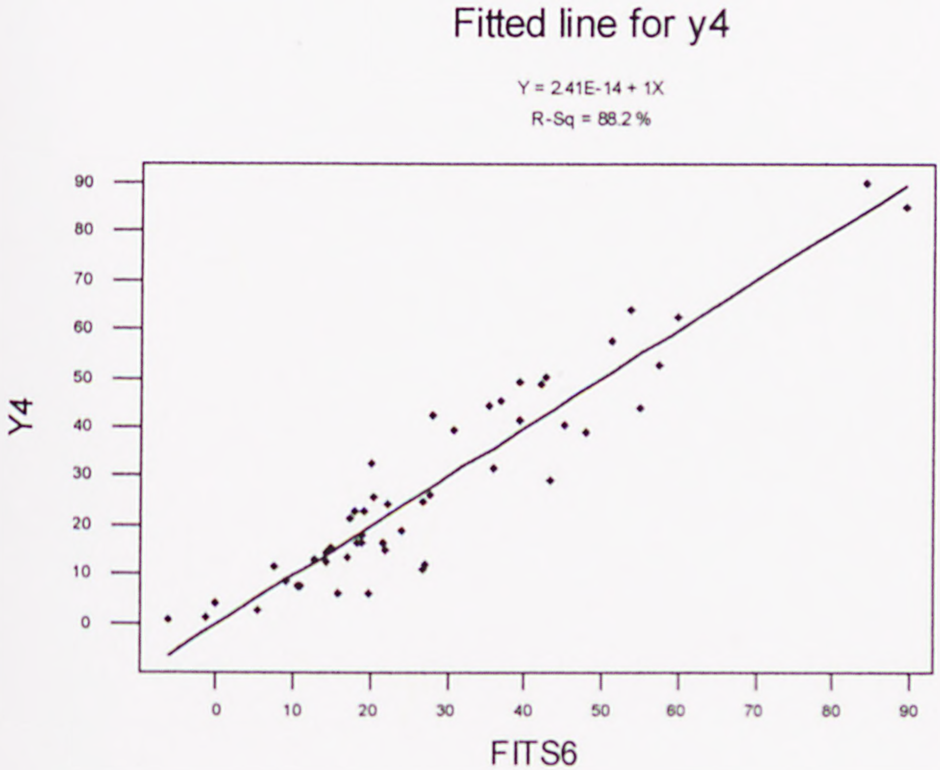
Source	DF	Seq SS
WBM	1	8640.4
Cretaceo	1	921.8
>100	1	796.9
Sect-Mud	1	352.6
WBM-Too	1	841.9
Too-Pale	1	134.0
Jur-20	1	46.8
Dep-Sect	1	264.2
Dep-Olig	1	333.2
Dep-Cret	1	3003.6
Dep-WBM	1	1975.6
Dep-Ins	1	1194.3
Dep-40	1	721.5

Unusual Observations

Obs	WBM	Y4	Fit	StDev Fit	Residual	St Resid
25	1.00	11.94	26.87	4.43	-14.93	-2.08R
38	1.00	11.14	26.72	4.67	-15.58	-2.21R

R denotes an observation with a large standardized residual


Residual plots for Y4
Normal Plot of Residuals
Residual
Normal Score
I Chart of Residuals
3.0SL=24.00
X=3.66E-14
-3.0SL=-24.00
Observation Number
Histogram of Residuals
Frequency
Residual
Residuals vs. Fits
Fit


Fitted line for y4
Y = 2.41E-14 + 1X
R-Sq = 88.2 %
Y4
FITS6

Regression Analysis

The regression equation is
Y5 = 188 - 198 WBM - 60.6 >100 + 5.73 Sect-Mud + 0.0521 Dep-Cret - 0.00347 Dep-Sect + 0.0204 Dep-WBM + 0.00658 Dep-40 - 0.0590 Dep-Olig - 88.3 Cretaceo + 31.6 Too-Pale - 3.13 Sect-PDC + 4.81 Sect-Jur

Predictor	Coef	StDev	T	P
Constant	188.44	19.01	9.91	0.000
WBM	-197.88	35.95	-5.50	0.000
>100	-60.588	9.743	-6.22	0.000
Sect-Mud	5.729	1.355	4.23	0.000
Dep-Cret	0.052149	0.006296	8.28	0.000
Dep-Sect	-0.0034709	0.0005211	-6.66	0.000
Dep-WBM	0.020429	0.006232	3.28	0.002
Dep-40	0.006579	0.001594	4.13	0.000
Dep-Olig	-0.059010	0.007817	-7.55	0.000
Cretaceo	-88.27	12.86	-6.86	0.000
Too-Pale	31.593	6.507	4.86	0.000
Sect-PDC	-3.1290	0.5408	-5.79	0.000
Sect-Jur	4.8089	0.9974	4.82	0.000

S = 8.802 R-Sq = 87.5% R-Sq(adj) = 83.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	12	19993.7	1666.1	21.51	0.000
Residual Error	37	2866.4	77.5		
Total	49	22860.1			

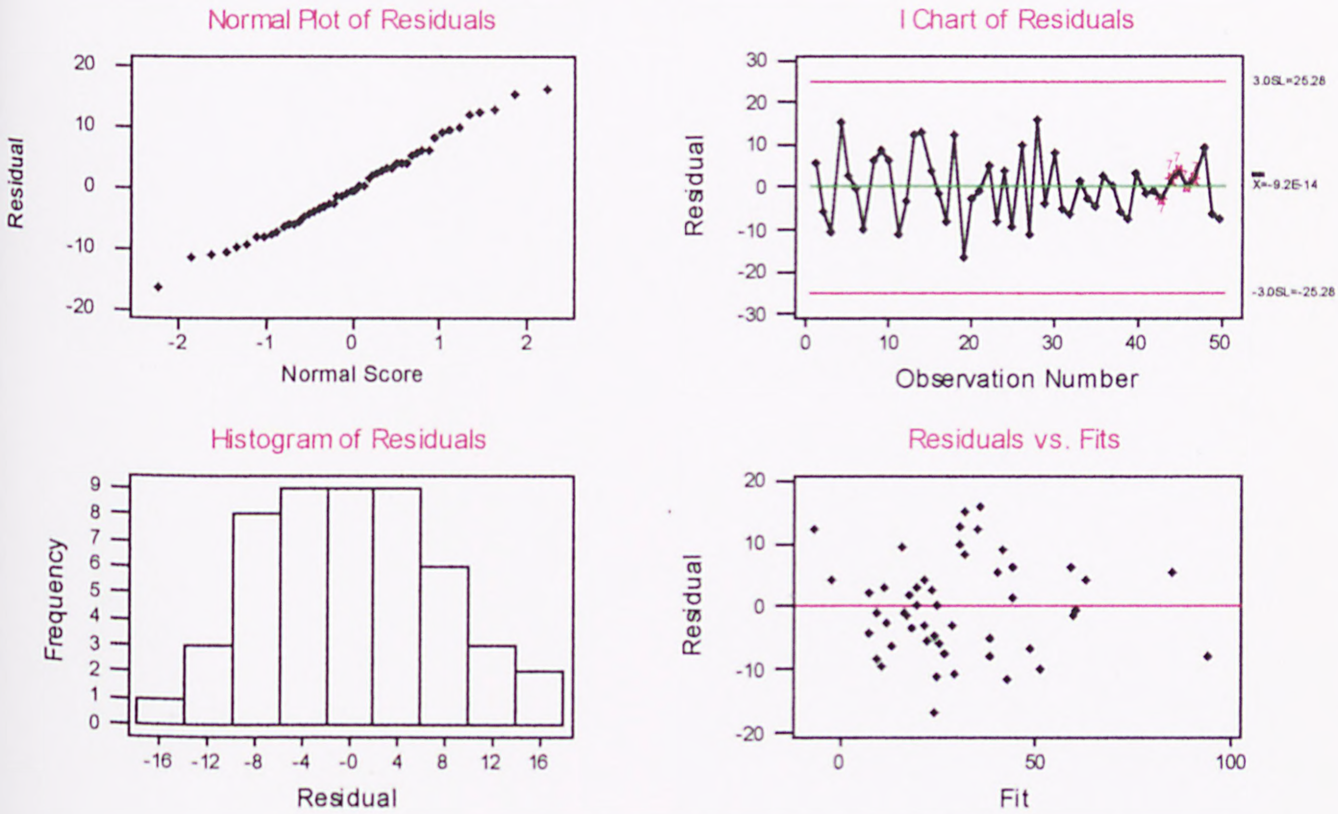
Source	DF	Seq SS
WBM	1	9076.9
>100	1	1186.3
Sect-Mud	1	1.7
Dep-Cret	1	2041.5
Dep-Sect	1	67.3
Dep-WBM	1	108.0
Dep-40	1	107.7
Dep-Olig	1	2309.8
Cretaceo	1	1844.1
Too-Pale	1	557.2
Sect-PDC	1	892.3
Sect-Jur	1	1800.9

Unusual Observations

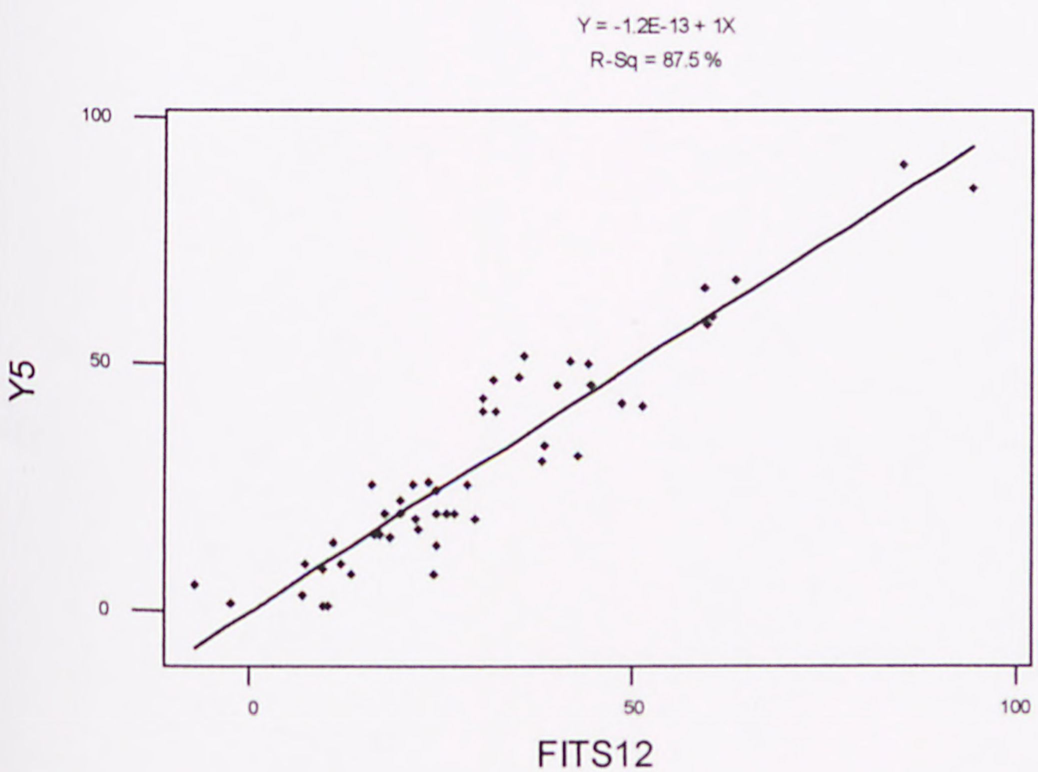
Obs	WBM	Y5	Fit	StDev Fit	Residual	St Resid
19	1.00	7.39	24.10	2.83	-16.70	-2.00R
28	1.00	51.77	35.62	4.94	16.15	2.22R

R denotes an observation with a large standardized residual

Residual plots for Y5



Fitted line for y5



Regression Analysis

The regression equation is
Y6 = 230 - 60.9 WBM - 0.126 Dep-Olig + 0.00669 Dep-40 - 0.0279 Dep-Too
- 0.00553 Dep-Jur +0.000003 Depth^2 - 156 Log-sec + 5.39 Sect-Too
+ 38.5 Ins-20 + 134 Ins-100 + 57.1 Olig-20 + 73.7 Olig-40 + 90.2 Olig-60

Predictor	Coef	StDev	T	P
Constant	229.98	43.45	5.29	0.000
WBM	-60.939	5.833	-10.45	0.000
Dep-Olig	-0.12605	0.01940	-6.50	0.000
Dep-40	0.006690	0.001632	4.10	0.000
Dep-Too	-0.027929	0.004461	-6.26	0.000
Dep-Jur	-0.005529	0.001640	-3.37	0.002
Depth^2	0.00000337	0.00000067	5.03	0.000
Log-sec	-155.75	35.25	-4.42	0.000
Sect-Too	5.3888	0.6008	8.97	0.000
Ins-20	38.462	6.729	5.72	0.000
Ins-100	134.11	19.75	6.79	0.000
Olig-20	57.14	14.70	3.89	0.000
Olig-40	73.71	14.70	5.01	0.000
Olig-60	90.18	19.21	4.69	0.000

S = 9.048   R-Sq = 88.4%   R-Sq(adj) = 84.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	13	22356.1	1719.7	21.00	0.000
Residual Error	36	2947.4	81.9		
Total	49	25303.5			

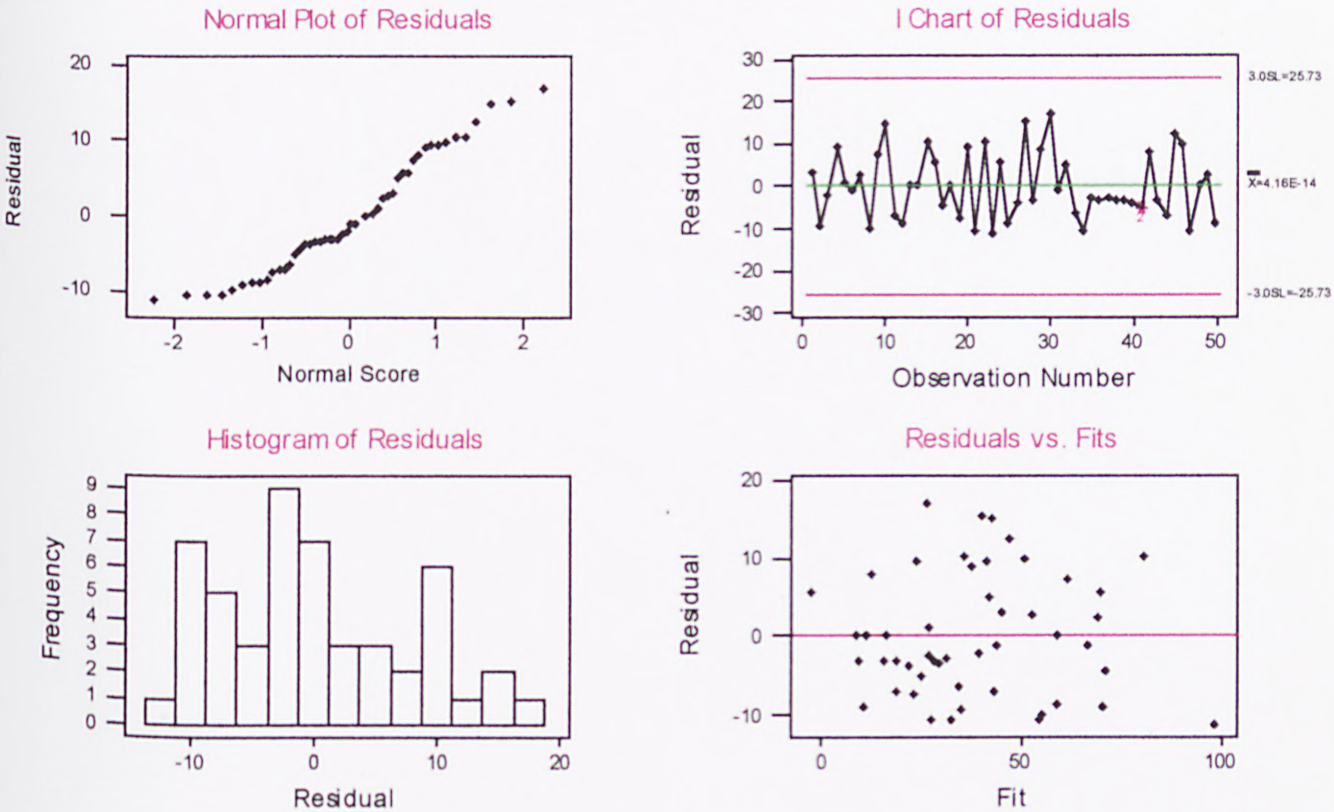
Source	DF	Seq SS
WBM	1	7608.8
Dep-Olig	1	3427.3
Dep-40	1	683.1
Dep-Too	1	367.1
Dep-Jur	1	1122.0
Depth^2	1	1847.6
Log-sec	1	41.4
Sect-Too	1	1720.2
Ins-20	1	1666.9
Ins-100	1	1659.5
Olig-20	1	3.0
Olig-40	1	405.0
Olig-60	1	1804.3

Unusual Observations

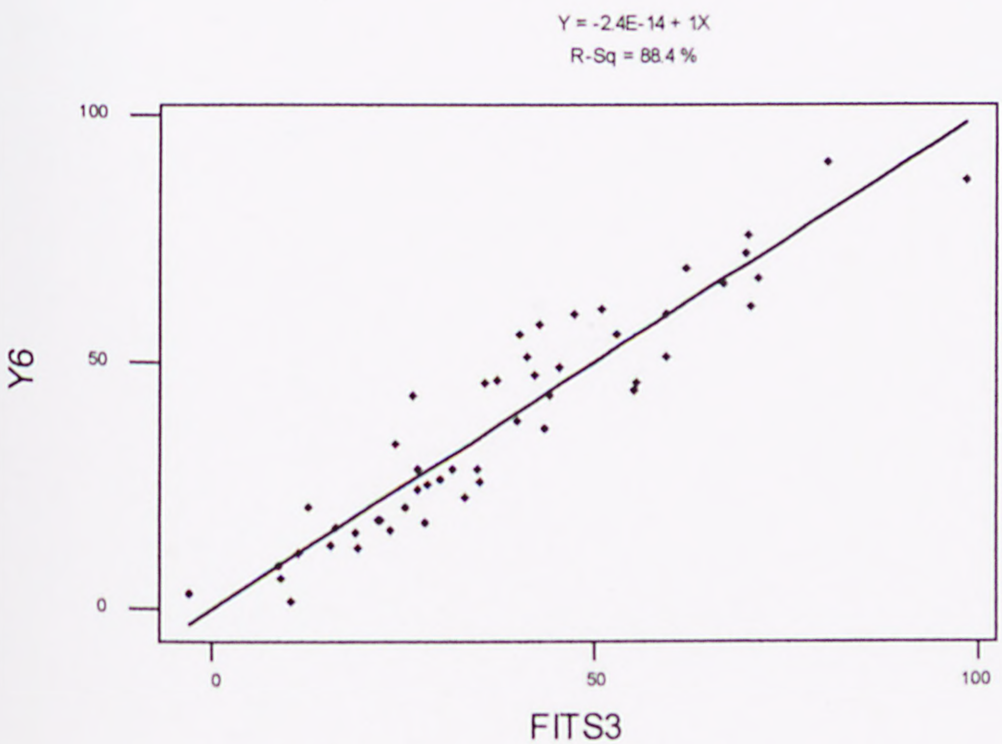
Obs	WBM	Y6	Fit	StDev Fit	Residual	St Resid
13	1.00	16.04	16.04	9.05	0.00	* X
14	1.00	11.14	11.14	9.05	0.00	* X
18	1.00	8.45	8.45	9.05	0.00	* X
30	1.00	43.21	26.23	3.48	16.98	2.03R R

denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

Residual plots for Y6



Fitted line for y6



Regression Analysis

The regression equation is
Y7 = 369 - 26.0 Section - 120 WBM - 143 Cretaceo + 0.812 Sect^2 + 5.50 Sect-Cre + 5.34 Sect-100 + 38.9 Ins-20 - 0.0474 Dep-Olig + 0.0267 Dep-Cret + 0.00830 Dep-40 + 1.78 Sect-Too + 20.5 Pal-20 - 0.00232 Dep-Sect + 0.0209 Dep-WBM + 0.884 Sect-60

Predictor	Coef	StDev	T	P
Constant	368.83	26.56	13.89	0.000
Section	-26.049	4.316	-6.04	0.000
WBM	-119.79	18.65	-6.42	0.000
Cretaceo	-143.35	27.62	-5.19	0.000
Sect^2	0.8124	0.1115	7.29	0.000
Sect-Cre	5.496	1.294	4.25	0.000
Sect-100	5.3394	0.5323	10.03	0.000
Ins-20	38.945	5.149	7.56	0.000
Dep-Olig	-0.047387	0.006725	-7.05	0.000
Dep-Cret	0.026730	0.004542	5.88	0.000
Dep-40	0.008299	0.001111	7.47	0.000
Sect-Too	1.7770	0.3042	5.84	0.000
Pal-20	20.512	3.666	5.60	0.000
Dep-Sect	-0.0023189	0.0004852	-4.78	0.000
Dep-WBM	0.020872	0.006752	3.09	0.004
Sect-60	0.8841	0.3657	2.42	0.021

S = 5.725   R-Sq = 95.4%   R-Sq(adj) = 93.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	15	23328.3	1555.2	47.45	0.000
Residual Error	34	1114.5	32.8		
Total	49	24442.8			

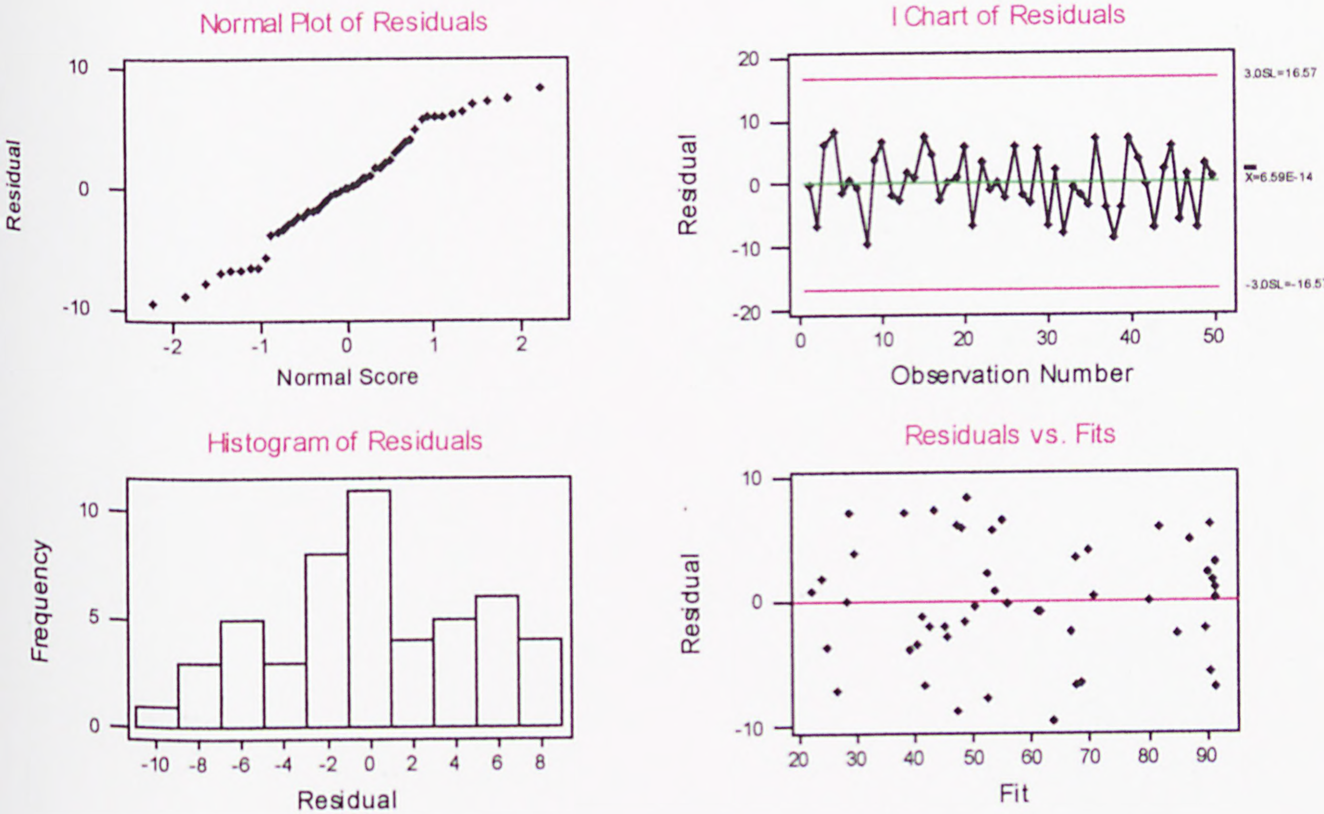
Source	DF	Seq SS
Section	1	1968.8
WBM	1	3907.6
Cretaceo	1	2192.9
Sect^2	1	5777.1
Sect-Cre	1	30.8
Sect-100	1	1102.8
Ins-20	1	1805.2
Dep-Olig	1	1522.6
Dep-Cret	1	394.6
Dep-40	1	593.7
Sect-Too	1	2510.3
Pal-20	1	267.7
Dep-Sect	1	703.9
Dep-WBM	1	358.8
Sect-60	1	191.6

Unusual Observations

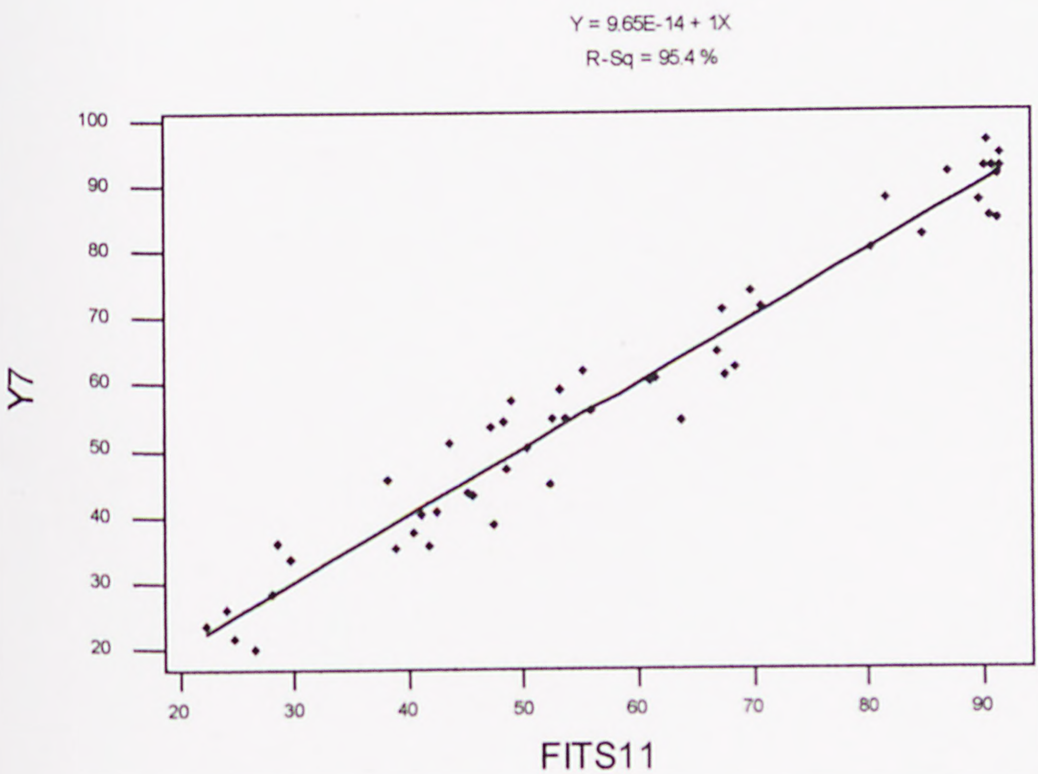
Obs	Section	Y7	Fit	StDev Fit	Residual	St Resid
18	17.5	80.400	80.400	5.725	0.000	* X

X denotes an observation whose X value gives it large influence.

Residual plots for Y7



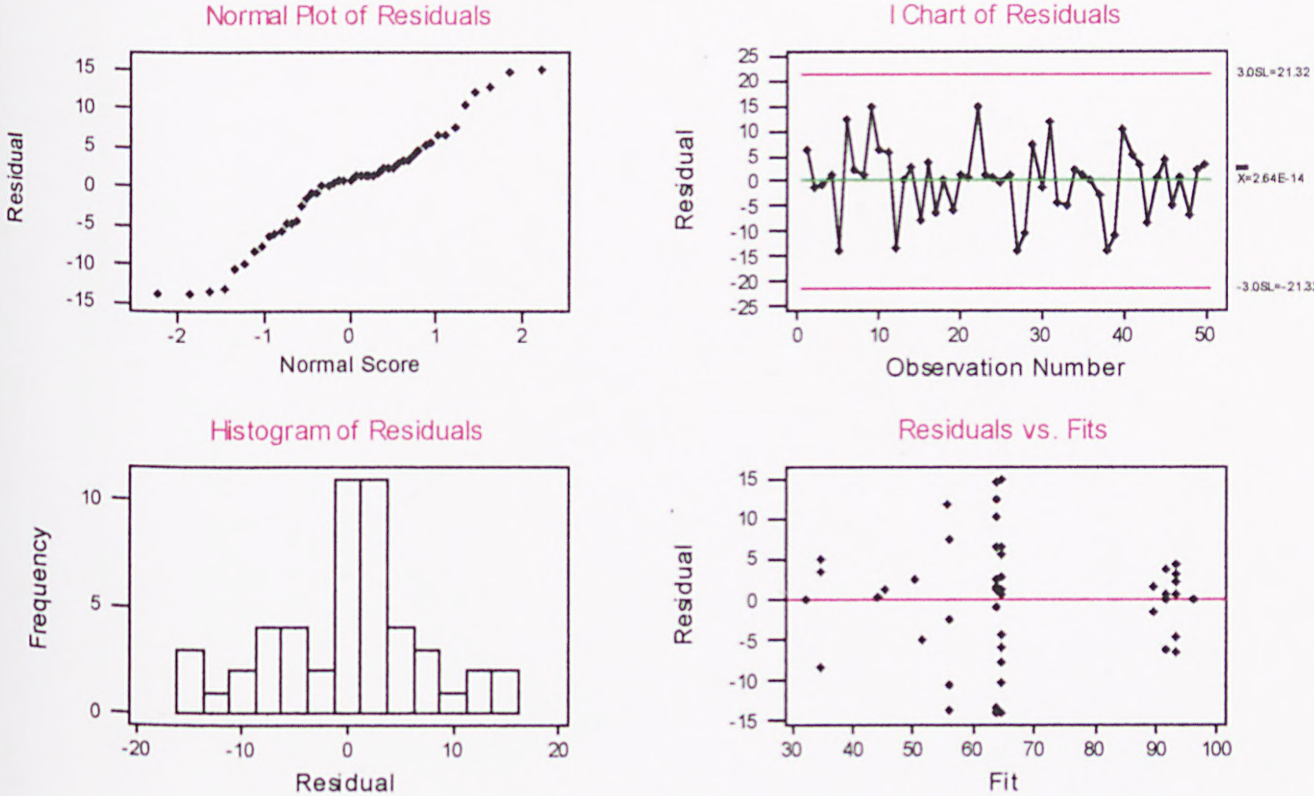
Fitted line for y7



Regression Analysis

```
The regression equation is
Y8 = 91.7 + 34.3 >100 - 8.89 WBM-Cret + 135 WBM-Jur - 14.1 Sect-Jur
           + 1.79 Sect-100 - 32.8 Olig-20 - 1.54 Sect-Mud - 0.0126 Dep-Quat

Predictor        Coef        StDev          T        P
Constant       91.707        3.713      24.70    0.000
>100           34.255        6.212       5.51    0.000
WBM-Cret       -8.887        2.737      -3.25    0.002
WBM-Jur        134.93        14.41       9.36    0.000
Sect-Jur      -14.126        1.443      -9.79    0.000
Sect-100       1.7944       0.4577       3.92    0.000
Olig-20       -32.818        8.010      -4.10    0.000
Sect-Mud      -1.5400       0.2331      -6.61    0.000
Dep-Quat    -0.012593     0.003180      -3.96    0.000

S = 7.740        R-Sq = 86.6%      R-Sq(adj) = 84.0%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         8     15879.7      1985.0     33.14    0.000
Residual Error    41      2456.1        59.9
Total             49     18335.8

Source       DF       Seq SS
>100          1       1017.5
WBM-Cret      1        535.3
WBM-Jur       1        673.6
Sect-Jur      1       7247.7
Sect-100      1        949.4
Olig-20       1       1121.2
Sect-Mud      1       3395.4
Dep-Quat      1        939.6

Unusual Observations
Obs        >100          Y8          Fit     StDev Fit     Residual     St Resid
 13        0.00       31.94        31.94          7.74         0.00          * X
 18        0.00       96.16        96.16          7.74         0.00          * X
 22        0.00       79.83        64.76          2.06        15.08        2.02R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.
```

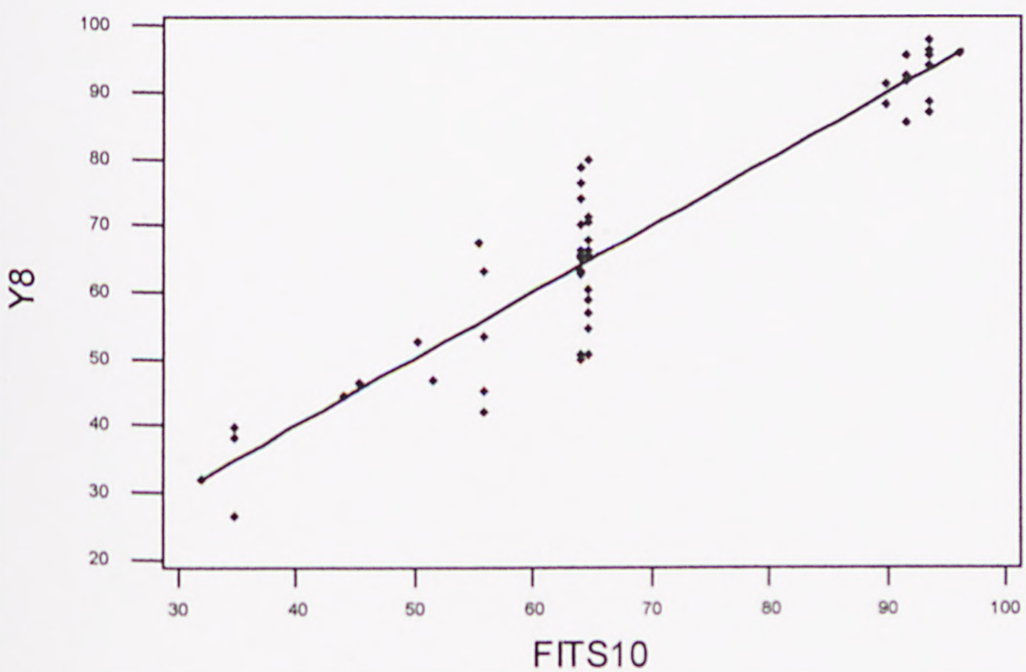
Residual plots for Y8



Fitted line for y8

Y = 0 + 1X

R-Sq = 86.6 %



APPENDIX.9: THE FORTRAN 90 PROGRAM.

!!$c This a program for the drill-cuttings size database

```
!!$c  Declare variables

       real sect,depth,log1
       real, dimension (1:9) :: y
       real, dimension (1:9) :: x
       integer rop,r20,r40,r60,r100,r200,strat,plio,mio,olig
       integer eoc,paleo,cret,jur,tria,quat,mud,bit
       integer tooth,insert,pdc,test,i,test2,max,ccent,cneg,test3
       x(1)=4.0
       x(2)=3.35
       x(3)=2.0
       x(4)=1.0
       x(5)=0.85
       x(6)=0.5
       x(7)=0.15
       x(8)=0.09
       x(9)=0.045

!!$c  Ask input data to the user

       write (*,*) 'Enter the section, the available choice is:'
       write (*,*) '23.5, 17.5, 12.25 and 8.5 (inches)'
       read (*,*) sect

!!$c  Set up obvious boundaries for section

       do while (sect .ne. 23.5 .and. sect .ne. 17.5 .and. sect .ne. 12.25
.and.&
              & sect .ne. 8.5)
              write (*,*) 'Please reselect the section from&
              & the presented choice'
              write (*,*) 'Enter the section, the available choice is:'
              write (*,*) '23.5, 17.5, 12.25 and 8.5 (inches)'
              read (*,*) sect
       end do

!!$c  Ask input data to the user

       write (*,*) 'Enter the stratigraphy drilled in that section'
       write (*,*) 'If there are several stratigraphies in the same &
       & section,'
       write (*,*) 'you need to run the program for each of them'
       write (*,*) '1- Pliocene, 2- Miocene, 3- Oligocene'
       write (*,*) '4- Eocene, 5- Paleocene, 6- Cretaceous'
       write (*,*) '7- Jurassic, 8- Triassic, 9- Quaternary'
       read (*,*) strat

!!$c  Deal with the dummy variable strat

       if (strat .eq. 1) then
       plio=1
       endif

       if (strat .eq. 2) then
       mio=1
```

```
        endif

        if (strat .eq. 3) then
        olig=1
        endif

        if (strat .eq. 4) then
        eoc=1
        endif

        if (strat .eq. 5) then
        paleo=1
        endif

        if (strat .eq. 6) then
        cret=1
        endif

        if (strat .eq. 7) then
        jur=1
        endif

        if (strat .eq. 8) then
        tria=1
        endif

        if (strat .eq. 9) then
        quat=1
        endif

!!$c  Set up obvious boundaries for strat

       do while (strat .ne. 1 .and. strat .ne. 2 .and. strat .ne. 3&
          & .and. strat .ne. 4 .and. strat .ne. 5 .and. strat .ne. 6&
          & .and. strat .ne. 7 .and. strat .ne. 8 .and. strat .ne. 9)
            write (*,*) 'Please reselect the stratigraphy from&
            & the presented choice'
            write (*,*) 'Enter the stratigraphy drilled in that &
            & section'
            write (*,*) 'If there are several stratigraphies in the &
            & same section,'
            write (*,*) 'you need to run the program for each of them'
            write (*,*) '1- Pliocene, 2- Miocene, 3- Oligocene'
            write (*,*) '4- Eocene, 5- Paleocene, 6- Cretaceous'
            write (*,*) '7- Jurassic, 8- Triassic, 9- Quaternary'
            read (*,*) strat
       end do

       if (strat .eq. 1) then
       plio=1
       endif

       if (strat .eq. 2) then
       mio=1
       endif

       if (strat .eq. 3) then
```

```
      olig=1
      endif

      if (strat .eq. 4) then
      eoc=1
      endif

      if (strat .eq. 5) then
      paleo=1
      endif

      if (strat .eq. 6) then
      cret=1
      endif

      if (strat .eq. 7) then
      jur=1
      endif

      if (strat .eq. 8) then
      tria=1
      endif

      if (strat .eq. 9) then
      quat=1
      endif

!!$c  Ask input data to the user

      write (*,*) 'Give the average depth (TVD in meters) for that &
      & stratigraphy'
      write (*,*) '(with a minimum value of 0m)'
      read (*,*) depth

!!$c  Set up obvious boundaries for depth

      do while (depth .lt. 0.0)
           write (*,*) 'Please redefine the average depth (TVD in &
           & meters) for'
           write (*,*) 'that stratigraphy (with a minimum value of &
           & 0m)'
           read (*,*) depth
      end do

!!$c  Ask input data to the user

      write (*,*) 'In this case, which drilling bit is used'
      write (*,*) '1- Tooth, 2- Insert, 3- PDC'
      read (*,*) bit

!!$c  Deal with the dummy variable bit

      if (bit .eq. 1) then
      tooth=1
      endif

      if (bit .eq. 2) then
```

```
       insert=1
       endif

       if (bit .eq. 3) then
       pdc=1
       endif

!!$c  Set up obvious boundaries for bit

       do while (bit .ne. 1 .and. bit .ne. 2 .and. bit .ne. 3)
          write (*,*) 'Please reselect the bit from&
          & the presented choice'
          write (*,*) 'In this case, which drilling bit is used'
          write (*,*) '1- Tooth, 2- Insert, 3- PDC'
          read (*,*) bit
       end do

       if (bit .eq. 1) then
       tooth=1
       endif

       if (bit .eq. 2) then
       insert=1
       endif

       if (bit .eq. 3) then
       pdc=1
       endif


!!$c  Ask input data to the user

       write (*,*) 'In this case, which mud is used?'
       write (*,*) '1- WBM, 0- SBM'
       read (*,*) mud

!!$c  Set up obvious boundaries for mud

       do while (mud .ne. 0 .and. mud .ne. 1)
            write (*,*) 'Please reselect the mud from the presented &
            & choice'
            write (*,*) 'In this case, which mud is used?'
            write (*,*) '1- WBM, 0- SBM'
            read (*,*) mud
       end do

!!$c  Ask input data to the user

       write (*,*) 'Enter the expected ROP for that stratigraphy:'
       write (*,*) '1- 0/20  2- 20/40  3- 40/60  4- 60/100  5- >100'
       read (*,*) rop

!!$c  Deal with the dummy variable ROP

       if (rop .eq. 1) then
       r20=1
       endif
```

```
      if (rop .eq. 2) then
      r40=1
      endif

      if (rop .eq. 3) then
      r60=1
      endif

      if (rop .eq. 4) then
      r100=1
      endif

      if (rop .eq. 5) then
      r200=1
      endif

!!$c  Set up obvious boundaries for ROP

      do while (rop .ne. 1 .and. rop .ne. 2 .and. rop .ne. 3 .and. &
           rop .ne. 4 .and. rop .ne. 5)
           write (*,*) 'Please reselect the expected ROP from&
           & the presented values'
           write (*,*) 'Enter the expected ROP for that stratigraphy:'
           write (*,*) '1- 0/20  2- 20/40  3- 40/60  4- 60/100  5 &
           & >100'
           read (*,*) rop
      end do

      if (rop .eq. 1) then
      r20=1
      endif

      if (rop .eq. 2) then
      r40=1
      endif

      if (rop .eq. 3) then
      r60=1
      endif

      if (rop .eq. 4) then
      r100=1
      endif

      if (rop .eq. 5) then
      r200=1
      endif

!!$c  Calculate the values for ys

      y(1)=0.87+14.0*quat+8.57*tooth*r20+0.00947*depth*cret&
           & -23.6*mud*cret+7.68*insert*r20-0.000283*depth*sect&
           & +0.00273*depth*mud+0.00440*depth*r40

      y(2)=19.8-12.1*sect*insert-22.6*insert*r40+20.3*jur&
           & *r20+0.0113*depth*mud+284*insert-55.4*mud&
```

```
      & +67.8*tooth+0.0443*sect*sect-24.6*r40-31.4&
      & *r200-0.0349*depth*insert-0.0270*depth*too&
      & -0.0318*depth*olig-0.00791*depth*jur+0.0124*depth*r40

 y(3)=75.6-3.87*sect-36.7*mud-59.6*cret+4.24*sect*tooth&
      & +0.0287*depth*cret-0.0341*depth*olig-0.0110*depth*tooth&
      & +0.00463*depth*r40+0.0692*depth*r100-0.0439*depth*r200&
      & +34.8*insert*r20

 y(4)=147-247*mud-76.2*cret-
      & 67.6*r200+7.99*sect*mud+26.0*mud*tooth&
      & +22.5*tooth*paleo+42.0*jur*r20-0.00306*depth*sect&
      & -0.0415*depth*olig+0.0429*depth*cret+0.0282*depth*mud&
      & +0.0107*depth*insert+0.00490*depth*r40

 log1=log10(sect)

 y(5)=188-198*mud-60.6*r200+5.73*sect*mud+0.0521*depth*cret&
      & -0.00347*depth*sect+0.0204*depth*mud+0.00658*depth*r40&
      & -0.0590*depth*olig-88.3*cret+31.6*tooth*paleo&
      & -3.13*sect*pdc+4.81*sect*jur

 y(6)=230-60.9*mud-0.126*depth*olig+0.00669*depth*r40-156*log1&
   5.39*sect*tooth+38.5*insert*r20+134*insert*r100+57.1*olig*r20&
      & +73.7*olig*r40+90.2*olig*r60-0.0279*depth*tooth&
      & -0.00553*depth*jur+0.000003*depth*depth

 y(7)=369-26.0*sect-120*mud-
      & 143*cret+0.812*sect*sect+5.50*sect*cret&
      & +5.34*sect*r100+38.9*insert*r20-0.0474*depth*olig&
      & +0.0267*depth*cret+0.00830*depth*r40+1.78*sect*tooth&
      & +20.5*paleo*r20-0.00232*depth*sect&
      & +0.0209*depth*mud+0.884*sect*r60

 y(8)=91.7+34.3*r200-8.89*mud*cret+135*mud*jur-14.1*sect*jur&
      & +1.79*sect*r100-32.8*olig*r20-1.54*sect*mud&
      & -0.0126*depth*quat

 y(9)=100

!!$c  Test the y values and notify the user

 test3=0
 cneg=0
 ccent=0

 do i=1,9

    if (y(i) .lt. 0) then
       test3=1
       cneg=cneg+1
    end if

    if (y(i) .gt. 100) then
       test3=1
       ccent=ccent+1
    end if
```

```
      end do

      if (test3 .eq. 1) then
          write (*,*) 'From the calculations,',cneg, 'y value(s)
          is(are) negative'
          write (*,*) 'and',ccent, 'y value(s) is(are) greater than
          100, therefore the interpolation'
          write (*,*) ' will significantly influence the output data.
          If more than 3 values'
          write (*,*) ' are in this case, you are advised to change
          your combination.'
      end if

!!$c  Do linear interpolation for outsiders

      if (y(1) .lt. 0) then
          y(1)=0
      endif

      test2=0

      do while (test2 .eq. 0)
         test2=1
         max=2

           do i=3,8
               if (y(i) .gt. y(max)) then
                max=i
               endif
           end do

           if (y(max) .gt. 100) then
              test2=0
              y(max)=y(max+1)+(((x(max)-x(max+1))/(x(max-1)-
              x(max+1)))*(y(max-1)-y(max+1)))
           endif

      end do

      test=0

      do while (test .eq. 0)
            test=1

            do i=2,8

               if (y(i) .lt. y(i-1)) then
               y(i)=y(i+1)+(((x(i)-x(i+1))/(x(i-1)-x(i+1)))&
               & *(y(i-1)-y(i+1)))
               test=0
               endif

            end do

      end do
```

```
      write (*,*) 'The values for the cumulative weight curve are: '
      do i=1,9
      write (*,*) 'x-value: ', x(i), 'correspondent y-value: ', y(i)
      end do


!!$c  Give advice for settlement properties


      write (*,*) 'If you are dealing with cuttings transport, we
      advise you to use'
      write (*,*) 'the following drag correlation applied to drill-
      cuttings:'

      write (*,*) 'Cd = 24/Rep + 39.88/exp(4.54 * Sph)'

      write (*,*) ' Please note that Rep is the Reynolds number of the
      particle and'
      write (*,*) 'that Sph is the sphericity factor. According to
      Chien 1994, for '
      write (*,*) 'most drill-cuttings, the average Sph is 0.8
      (0.7924). If you have'
      write (*,*) ' the sphericity factor for each range of size, just
      enter it in Cd.'

      stop

      end
```

APPENDIX.10: EXPERIMENTAL WORK SUPPORTING PROTEUS (BMT NEWSLETTER).

FOCUS ON NEW TECHNOLOGY

EXPERIMENTAL STUDIES SUPPORTING THE PROTEUS DRILL MUD AND CUTTINGS DISPERSION MODEL

Continuing the series of articles on the development and validation of the PROTEUS offshore discharge model, Linda Carles at Robert Gordon University outlines the on-going studies supporting the modelling of drill mud and cuttings modelling.

Linda Carles characterising cuttings samples during offshore drilling operations

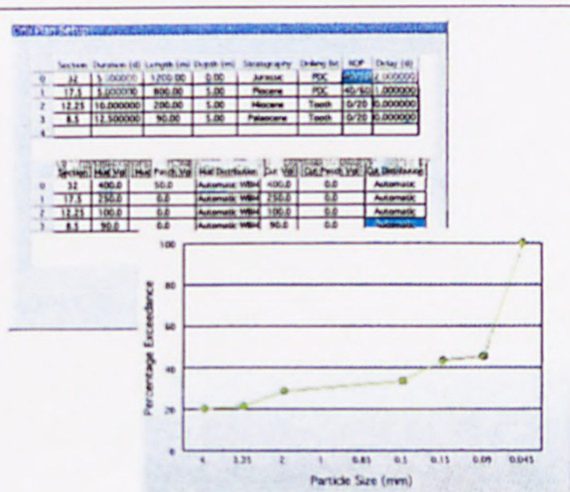
The PROTEUS drill mud/cuttings model has been developed to simulate the dispersion of exploration discharges and subsequently disturbed cuttings piles. Central to accurate simulation is knowledge of the characteristics of discharged particulates, in particular the distribution of particle sizes and the speed of settling to the seabed. Existing models of mud/cuttings dispersion rely on the user-entered values for size distributions and settling speeds. However, this information is extremely difficult to determine with the diverse range of cuttings sizes and characteristics arising from the drilling operations.

Over the past two years, studies at Robert Gordon University have focused on the characterisation of particulate distributions and determination of realistic settling velocities for drilling discharges. Extensive offshore surveys have been conducted with the close co-operation of Total Oil Marine, Elf Caledonia, Conoco, Arco, Baroid and Saga Petroleum. During the drilling operation material has been sampled just prior to discharge and characterised in terms of size, shape and density. Concurrently, detailed logs have been maintained on the drilling conditions at the time of sampling. Back in the laboratory, the samples have been used in settling experiments where individual particles are tested in a 1.50 m tank using high speed video to record and measure the settling velocity.

The key innovation in the work carried out has been the correlation between the operational drilling parameters and the cuttings size distributions arising. A large number of size distributions have been correlated with stratigraphy, drill bit used, rate of penetration, section, section depth and mud type. These parameters have been found to substantially describe the size distribution of cuttings arising from the drilling and have been encapsulated in a predictive model. Instead of entering settling velocity data, the user can now describe the drilling operation in terms of these parameters from which reliable cuttings distributions can be predicted and used in the modelling. The settling speed data from the laboratory experiments has also been used in the validation of algorithms used in PROTEUS to predict settling velocity on the basis of particle size and density.

The experimental studies are currently completing with examination of the disaggregation of particulates after discharge. The widespread use of water-based drilling muds results in rapid separation of muds from cuttings once the particles enter the water. This leaves the cutting exposed to ingress of water into the particle matrix which can, depending on the particle composition, lead to disaggregation of the particle. This has significant implications for the subsequent transport of particulates which may change from large 'chunks' of rapidly deposited material, to a fine 'cloud' of small particles with a small settling speed resulting in far wider dispersion. Observations suggest that this process may occur in a matter of a few minutes on cuttings from soft clay formations.

The detailed studies over the past two years have enabled the development of a highly user-orientated model configuration supported by validation measurements. For the first time, readily available information can now be used to set-up realistic offshore discharge model simulations.



Drill plan set-up dialog from PROTEUS and typical cutting size distribution arising