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A New Approach to Calculate the Optimum Placement of Centralizers includes Torque and Drag Predictions

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Abstract

A good primary cementation requires careful selection of centralizers and their placement on the string. The centralizer placement algorithm described in the API-10D was corrected and put into a computer program. The standoff value is calculated based on the actual borehole geometry, string data and centralizer performance. The model was enhanced by a newly developed drag force simulation taking the centralizer running force into account. Additionally, the prediction of the expected torque values for rotating liner applications is included.

1 Introduction

The key factor for a successful cementation job is the replacement of the mud in the wellbore by the cement slurry. Hydraulic considerations call for the need of a good centralization of the string for all sections in which a good cementation is required. Centralizers have been used for decades to fulfill this job. Throughout the past couple of years, more and more designs of highly inclined, including horizontal, wells incorporate cemented production casing and liner sections. In these cases, the optimum placement of centralizers is achieved by balancing between a high standoff ratio and low drag forces.

A mathematical simulation model is used to calculate the optimum spacing of centralizers to obtain the best standoff at a given borehole location.

This model takes into account relevant factors, such as:

- the lateral force at any given location based on borehole geometry, buoyed string weights and tension forces
- the centralizer's reaction to these forces, based on test data for each pipe size/hole size combination
- the sag between centralizers based on the elasticity of the pipe and a three-dimensional vector analysis of the weight and tension components.

This mathematical model is associated with a torque and drag analysis, utilizing the known running forces of the centralizers and the friction factors that depend on the mud type. This analysis is important in order to evaluate whether the desired centralizer spacing can be run or rotated without creating problems due to high drag forces, or damage to the pipe connections. The equations upon which these models are based and the computer algorithms used are described in this paper.

2 Maximize Standoff and Minimize Drag

Various models have been described in the literature to calculate the centralizer placement [1], [2].

The criteria to select a centralizer pattern should be not only the achieved centralization but, especially in highly inclined wells, the ability to move the string. Thus, drag and torque calculation should be a part of the centralizer placement calculation.

It is important to understand that all mathematical equations and relationships regarding centralizer placement describe a model situation only. The actual standoff in a borehole depends on many different factors. There is no method of actually looking into the well and no tool like a "Standoff-Logging-Tool" to provide this information directly. Some logging methods, such as the Cement Bond Log, give a secondary indication about the standoff by determining the success of the cementation. The definite measurement of the actual standoff, however, is not practical. As can be seen in section 5, actual field cases show that the models do come close to real situations.

2.1 Basic Steps for Centralizer Placement

The optimum centralizer placement calculations for highly inclined wells follow a scheme as described below:

STEP 1	select an appropriate centralizer
STEP 2	select a practical centralizer spacing
STEP 3	calculate the lateral load at each centralizer location
STEP 4	calculate the centralizer deflection
STEP 5	determine the sag between the centralizers
STEP 6	calculate the total torque- and drag forces
STEP 7	change the centralizer type or the spacing according to the needs
STEP 8	go back to step 2 until an optimum balance between a good standoff and an acceptable low drag force is reached (trial and error).

This loop can be performed manually by changing the variables in the calculation until the optimum solution was found. It is also possible to automatically adapt variables in these algorithms in an intelligent way to perform this iteration by a computer program.

2.2 Definitions

2.2.1 Centralizer Forces According to API-10D

The centralizer deflection is calculated by using the results of the restoring force test performed according to API. Specification 10D [2].

This API Specification defines the forces related to bow spring centralizers and their use in the borehole. According to this specification, the purpose of the centralizer is "to facilitate running casing to the desired depth, and to assist in centering the casing in the borehole".

The capability of a spring bow centralizer to push the pipe radially away from the borehole wall towards the center of the borehole is defined by the restoring force.

The restoring force causes a friction force on the borehole wall. This is the so called running force (also: moving force).

The starting force is the force that is required to push a centralizer into the previously set casing.

It is obvious that under operational aspects the moving force and the starting force should be kept at a minimum while a high restoring force is desired to achieve a centralization as high as possible.

2.2.2 Normal Force (Lateral Load)

The normal force vector is the perpendicular force on a pipe section or on a centralizer at a particular position. The compression of a bow-type centralizer depends on the normal force. Additionally, the normal force is used in the torque- and drag calculation.

The normal force vector is the combined force of the vertical weight component of the buoyed string and the tension component at a particular point perpendicular to the borehole axis. If the so called "softstring" model is used, it is assumed that the force needed to bend the string around a dogleg can be neglected. This is true for long radius and medium radius buildup rates. If a casing or a liner is to be run into a short radius build-up section or a high dogleg, the "softstring" model still can be used. In this case, a higher drag force may be approximated by incorporating a larger friction factor than normal in the curved section.

The weight component as well as the tension below a particular point for which a normal force calculation is made are based on the buoyed weight of the string. The process of mud removal is most critical when the cement has just reached the shoe and the mud displacement process begins. Consequently, the buoyancy factor should be calculated using the mud weight outside the pipe and the cement weight inside.

2.2.3 Sag between Centralizers

The sag between the centralizers can be calculated in different ways. All methods are based mainly on a "chain-line" type equation, taking into account the buoyed weight of the pipe. Former API specifications issued before published the so called "hinged end" solution, in which each pipe section between two centralizers was regarded as an individual pipe with no connection to the preceding or the following one. Juvkam-Wold et al. described in the SPE paper 21282 [1] a different way to calculate the sag. Since each pipe section is connected to other sections in the string, they describe a set of equations using a "fixed end" method. As will be shown later, the equations presented in that paper required corrections in order to achieve an algorithm that can be applied practically to calculate the sag.

2.2.4 Friction Coefficients

The friction- coefficients (also: friction factors) of the material configurations pipe/formation, pipe/pipe, centralizer/ formation and centralizer/pipe are used to estimate the drag force and the resistance against rotation. In the literature [3]-[5] it has been described that friction factors depend on several unknown parameters such as small doglegs, ledges and the surface roughness of the borehole wall. The dependency of the type of mud (oil-based mud or water-based mud) is more significant for the magnitude of the friction factor than the material configuration itself (steel/formation, steel/steel, etc.). Figure 1 shows the applicable range of friction factors for different types of mud systems. These literature- and experience-based values show a friction factor range of approximately 0.25 to 0.35 for a water-based mud, whereas an oil-based mud may range among 0.15 and 0.25. These figures may vary from region to region and depend on the hole conditions. They are subject to adjustment on a history matching basis.

These "practical" friction factors do not directly correspond to values determined in small scale laboratory tests, for example according to the API Recommended Practice Standard Procedure for Testing Drilling Fluids [6]. Friction factors observed in the field or in large scale laboratory tests may be ten times higher in magnitude.

2.3 Standoff Considerations

The standoff is defined as the relationship between the distance (annulus clearance) between pipe and borehole wall when the pipe is fully centered and the actual minimum distance under normal force and sag conditions. The standoff is expressed as a percentage of the annulus clearance. A standoff of 100 % is reached, when the axis of the pipe exactly meets the axis of the borehole. The pipe body touching the borehole wall results in 0% standoff. The standoff is directly associated with the relationship of the open areas for hydraulic flow. While the total flow area as the open space between pipe and borehole wall is constant (provided a constant pipe diameter and a gauge hole) a pipe that is not centered creates different flow areas around the pipe body. As the area is reverse proportional to the flow resistance, the cement slurry may try to find the way of least resistance and mud pockets might remain. A high standoff therefore is desirable [7], [8]. While some old literature states that 67% is an adequate standoff, industry experiences have indicated that higher values have are desirable. Standoff values of 75 to 90% can be achieved without compromising the drag forces.

2.4 Drag Calculations

Drag force analysis provides the information if the liner or casing can be run to bottom without incident.

Drag models published in the past did not take centralizer running and starting forces into account (for example [9] and [10]). The running force of a spring bow centralizer will add some amount of force to the drag based upon the normal force and the friction factor. It is, however, not the case, that the running force may simply be added to the drag force caused by the normal force vector. As is shown in section 8.1 a vector analysis of the resulting radial forces of a spring bow centralizer consisting of several bows results in either the running force to be used in the total drag force analysis or the drag force based on the normal force, whichever is higher.

The total drag force can be shown graphically in a hookload prediction diagram. It is obvious that a high drag force in the horizontal section can lead to a condition where the weight of the string above this section is not high enough to push the casing or the liner in place. If the drag forces exceed the block weight available at the surface, the string cannot be run further.

2.5 Rotational Torque Model

Rotating a casing or a liner improves the mud removal during cementation.

A simple method may be used to calculate the rotational torque for a casing or a liner string. The model uses the normal force vector and the friction factor between the inner side of the centralizer collar and the outer radius of the pipe to calculate the resistance against rotation. By accumulating the torque starting from the shoe up to the rotary table, a prediction can be made as to whether the rotation of a string is possible in a given configuration and if a connection at a particular location within a string can withstand the rotation without being overtorqued.

3 Mathematical Solutions

The mathematical solution to calculate the optimum spacing of centralizers is based on various input parameters. Basically, string data, hole data, fluid data as well as centralizer data are used for the calculation.

Each well data file contains the casing or liner sizes as they are run into the well. Each individual string is called a "job". The succeeding smaller casing size takes data from the previous job, if applicable. For example the inner diameter of the previous casing is used as input for the next casing string.

A common well data file contains measured depth, inclination and azimuth for all jobs from the surface down to the total depth.

To allow a wide choice of variations, each string can be divided into a number of sections (currently up to 50). In each section, parameters such as pipe size, pipe weight, centralizer parameters and hole size can be adjusted. Table 1 shows the possible parameter variations and their influence on standoff, drag and torque.

3.1 Revised Existing Standoff Model

As a basis for the standoff calculation, the equations given in API-10D [2] are used. This set of equations uses a three-dimensional normal force vector to calculate the load on a centralizer and makes use of the "fixed end" model regarding sag calculation.

During the development of the mathematical model, some errors were found in those equations. The corrections to the API Specification 10D are explained by showing the main parts of the basic formulas used in API Specification 10D. Also, the nomenclature of that specification is used so that no separate nomenclature is stated in this paper. The numbers of the equations shown in this paper correspond directly to the numbering system used in the API Specification 10D.

3.1.1 Casing Deflection in 1D, straight, inclined Wellbores without axial Tension

In an inclined wellbore without doglegs and with negligible axial tension or compression in the casing, the casing deflection at the midpoint between two centralizers is given by

$$\delta = \frac{W_e L^4 \sin\bar{\theta}}{384\,EI} \qquad (7)$$

This equation remains unchanged.

3.1.2 Casing Deflection in 1D, straight, inclined Wellbores with axial Tension

Under the effect of axial tension in the casing string, the casing deflection may be calculated by Timoshenko's [11] equation for the deflection of a straight tie rod:

$$\delta = \left(\frac{qL^4}{384\,EI}\right)\left(\frac{24}{u^4}\right)\left(\frac{u^2}{2} - \frac{u\cosh u - u}{\sinh u}\right) \qquad (8)$$

where $u = \sqrt{\dfrac{TL^2}{4EI}}$ .... (9)

with $q = W_e \sin\bar{\theta}$ as the uniformly distributed lateral force.

This equation remains unchanged.

3.1.3 Casing Deflection in 2D, drop-off Wellbores

The wellbore lies in the vertical plane with the wellbore inclination angle decreasing as the measured depth increases. The wellbore has a constant curvature between any survey points. When we consider furthermore total equivalent uniformly distributed lateral force, which includes both the lateral components of casing weight and axial tension, the casing deflection is given by

$$\delta = \left(\frac{NL^3}{384\,EI}\right)\left(\frac{24}{u^4}\right)\left(\frac{u^2}{2} - \frac{u\cosh u - u}{\sinh u}\right) \qquad (12)$$

with N as the total lateral load on the casing span between two centralizers. N is given by

$$N = W_e L \sin\bar{\theta} + 2T\sin(\beta/2) \qquad (13)$$

This formula has been corrected by substituting the "-" sign with a "+" sign.

3.1.4 Casing Deflection in 2D, buildup Wellbores

The wellbore lies in the vertical plane with the wellbore's inclination angle increasing as the measured depth increases. Casing deflection is calculated by the equation

$$\delta = \left(\frac{NL^3}{384\,EI}\right)\left(\frac{24}{u^4}\right)\left(\frac{u^2}{2} - \frac{u\cosh u - u}{\sinh u}\right) \qquad (15)$$

in this case N is given by

$$N = W_e L \sin\bar{\theta} - 2T\sin(\beta/2) \qquad (16)$$

This equation remains unchanged.

3.1.5 Casing Deflection in 3D Wellbores

The resulting casing deflection in the 3D wellbore is the vector summation of the deflection in principal normal and the binormal directions of the wellbore [1]. The component in tangent direction is usually much smaller than the component due to axial tension and may be neglected.

$$\delta_{dp} = \left(\frac{\sqrt{N_s^2 + N_p^2}\, L^3}{384\, EI}\right)\left(\frac{24}{u^4}\right)\left(\frac{u^2}{2} - \frac{u \cosh u - u}{\sinh u}\right) \qquad (21)$$

This formula was corrected by dividing by 384EI instead of 348EI.

where $N_s = W_e\, L \cos\gamma_n + 2T\sin(\beta/2)$ ....(17)

$$\cos\gamma_n = \frac{1}{\sqrt{\sin\beta \cdot \sqrt{2} \cdot \sqrt{1+\cos\beta}}} \cdot \begin{pmatrix} \sin^2\theta_1 \cdot \cos\theta_2 - \sin^2\theta_2 \cdot \cos\theta_1 - \\ \sin\theta_1 \cdot \sin\theta_2 \cdot (\cos\theta_1 - \cos\theta_2) \cdot \\ \cos(\phi_1 - \phi_2) \end{pmatrix} \qquad \text{..............(18)}$$

and

$N_p = W_e\, L \;\; \cos\gamma_m$ ....(19)

$$\cos\gamma_m = \frac{\sin\theta_1 \cdot \sin\theta_2 \cdot \sin(\phi_2 - \phi_1)}{\sin\beta} \qquad \text{..........................(20)}$$

Compared to the original API-10D equations, the factor $\cos\gamma_n$ ***is mathematically derived in a different way, which we believe to be correct.***

3.2 Drag Calculations based on Normal Force and Centralizer Forces

The total drag force encountered when running a string is a combination of the normal force times the friction factor and the running force of the centralizer for the given pipe-size/hole-size combination.

An analysis of the centralizer forces (see appendix 8.1) shows that the running force is the resulting friction force caused by centralizer bow springs in contact with the borehole wall. When the centralizer is deflected towards one side by the normal force, the bows on that particular side receive a higher load. On the other side the same load is taken away from the bows, resulting in the same running force as before. Therefore, the drag force can be approximated by using the running force of the centralizer until the drag force calculated by the normal force times friction factor exceeds the centralizer running force. This is taken into account in the mathematical drag model by selecting either the running force or the normal force times friction factor, whichever is higher.

The running force is measured by procedures in API-10D [2]. The contact surface between the actual borehole (or the previous casing) wall and the spring bow is replaced by a steel to steel contact in the test setup. In these tests, lubrication with an API modified grease allows defined friction conditions and repeatable results. To compensate for real downhole conditions, the running force receives a friction factor correction in the drag force analysis.

Additionally, the running force is adjusted in proportion to changes in the borehole diameter. A linear relationship is assumed between the borehole diameter and the running force. In a smaller diameter, the running force is higher; a larger hole will result in a lower running force. This is true for the linear range of the single spring bow characteristics and still is within an acceptable range for any non-linear portion of that curve.

The drag force is calculated taking the actual string data as well as the actual borehole situation into account. The drag force is calculated for each individual string portion lowered into the borehole.

For each string element equipped with a centralizer entering the previous casing, the starting force is taken into account instead of the running force. Also the starting force value is corrected for friction and diameter.

Combined with the buoyed string weight component in the deviated well, the drag force leads to a hookload prediction for the string being lowered into the borehole (Figure 2). For each depth value, the static hookload, upstroke and downstroke values are graphically plotted. The block weight is incorporated into this calculation as the weight value at the rotary table.

3.3 Torque Model based on Normal Forces

With the data given in the standoff calculation, an elementary torque estimation can be calculated easily (see appendix 8.2). This elementary calculation has been compared to other models and found to be acceptable for field use.

Comparison of torque estimates to the maximum allowable torque value of the casing connections will determine the feasibility of rotating the string.

4 Computer Model

4.1 User Interface

The centralizer placement algorithms are put into a computer program called CentraPro Plus™. The program is based on the current industry PC standard and makes use of the general conventions regarding pull down menus and data entries allowing a fast and user-friendly calculation of the optimum centralizer placement. In accomplishing the required task, the program guides the user intuitively. The program is written entirely in 'C' language.

The less experienced user is assisted by a menu guiding him through the necessary steps to quickly enter all data and achieves an instant output.

A spreadsheet-type calculation system with input/output cells enables the advanced user to change the default data and arrive at a more individualized engineering solution.

Instant graphical representation of selected variables illustrates the effect of changes made. This allows the user to optimize the selection and placement of centralizers to obtain the best possible primary cementation and mud removal. Figure 3 shows a screen shot of the main spreadsheet screen including the graphics.

Borehole data such as measured depth, inclination and azimuth may be imported in a pre-defined ASCII format. This allows data to be transferred through electronic mail or by exchanging discs preventing possible input errors.

All data contained in the spreadsheet can be exported as an ASCII file, so that results can be processed and used in other applications.

4.2 Mathematical Module and Databases

All relevant centralizer data and pipe information are stored in databases. This minimizes the possibility of human input errors. Each well data file contains all relevant data on each casing or liner string (called 'jobs'). Each job may be divided into sections that allows the variation of parameters such as hole size, centralizer type and spacing, friction factors and pipe parameter.

The number of steps required to perform the calculations is minimized by a large amount of prerecorded data. This includes a centralizer database containing all relevant centralizer data and a large tubular database containing nearly 1000 combinations of size and weight. This minimizes the possibility of human errors.

All options such as units of measurement, output format and default centralizer can be individually set and stored for future use. This allows custom designed data handling.

4.3 Report Module

Results of the simulation are presented in a way that can easily be read and interpreted. A complete overview about the standoff, required number of centralizers and stop collars, as well as the torque and drag figures is printed in tabular as well as graphical format.

A language module added to the program allows the report to be printed out in any language. Translation of the titles and figures is simply added in a separate file. Different fonts can be used to print the report for the use in countries where English is not the principal language for oilfield use (for example Russia).

5 Model Calibration based on Field Cases

The predicted standoff in a given borehole configuration cannot be verified directly. No practical means exists to measure the standoff downhole. Verification must be done using secondary methods. One method is to correlate the cementing success to the predicted standoff values. The judgment on the cementing success can either be based on logging results, for example from cement bond logs, or on other technical methods, such as pressure tests. This relationship between good standoff values and a good cementation and vice versa has been presented in prior literature (for example in [7] and [8]).

The standoff calculation in the model used is based on the normal force, also called lateral load. The drag calculation also is partly based on the normal force value. The drag force can be directly measured by observing the upstroke and downstroke hookload.

A valid conclusion is, that if the drag force and torque prediction are correct, the standoff calculation based on the same parameters is also likely to be correct.

Individual comparisons of predicted hookload values compared to actual ones show a good correlation, as depicted in Figure 2. The figure shows the upstroke and downstroke hookload of a 7" liner run into a horizontal well.

Figure 4 shows the crossplot of various hookload predictions (y-axis) compared to actually measured hookload values (x-axis) during casing and liner running. The linear trendline in this crossplot shows the excellent correlation between these two data sets.

6 Conclusions and Future Outlook

A good cementation requires careful planning and includes the selection of centralizers and their placement on the string. Mathematical models were developed and described.

The set of equations described in API Specification 10D were revised, corrected and put into a powerful computer algorithm. The output of this part of the model gives the standoff value based on the borehole geometry, string data and centralizer performance.

An important part of the centralizer placement procedure is the prediction of the expected drag forces, especially for highly inclined wells such as horizontal wells.

The model was enhanced by a newly developed algorithm to calculate the drag force while running the casing and liner based on the normal force, the centralizer running force and on the friction factor. This algorithm allows the prediction of the expected torque values at each location within the string for rotating liner applications.

The comparison of the predicted figures with actual field cases allows the verification of the validity of the model.

Although the set of equations used for the standoff prediction and the torque and drag model are elementary, the results have been shown to allow a fast and reliable prediction for field use.

The computer program derived from these equations now is in use in over a hundred installations worldwide. The practical use of this program in the day-to-day business of cementing engineers will allow a fine tuning of the models used. Additional feedback from rotating liner applications is needed to prove the validity of the torque predictions.

The application of standoff predictions in combination with a torque and drag analysis taking into account running and starting forces of centralizers allows the safe and economical running of highly inclined and horizontal casing and liner strings.

Due to the modular design of the software and a computer language that is commonly used for professional applications it is possible to enhance the program and incorporate other modules such as a hydraulic mud replacement simulator.

7 Literature

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CentraPro Plus is the trademark of Weatherford

8 Appendix

8.1 Running Force Considerations

The deflection of a centralizer due to the normal force does not have any influence on the running force. This is shown in this section.

The running force for a centralizer with 6 bows can be calculated as follows (see figures 5 and 6):

$$F_F = F_R = F_{B-total} \cdot \mu \quad \text{(8.1-1)}$$

$F_F =$ friction force

$F_R =$ running force

$F_{B-total} =$ total radial spring bow force

$\mu =$ friction factor

$n =$ number of bows

The spring bow force for each bow is:

$$F_{Bn} = S_{Bn} \cdot C_f \qquad (8.1\text{-}2)$$

F_{Bn} = radial spring bow force
S_{Bn} = compression of bow n
C_f = spring bow constant

If the centralized pipe is in a central position (100% standoff) the radial forces of all centralizer bow are equal (see figure 6):

$$F_{B1} = F_{B2} = F_{B3} = F_{B4} = F_{B5} = F_{B6} \qquad (8.1\text{-}3)$$

The total spring bow force is

$$F_{B-total} = \sum_{n=1}^{6} F_{Bn} = 6 \cdot F_B \qquad (8.1\text{-}4)$$

According to equations 8.1-1, 8.1-2 and 8.1-4 the running force for a non deflected centralizer equals:

$$\begin{aligned} F_R &= F_{B-total} \cdot \mu \\ F_R &= 6 \cdot F_B \cdot \mu \qquad (8.1\text{-}5) \\ F_R &= 6 \cdot S_B \cdot C_f \cdot \mu \end{aligned}$$

For a centralizer deflected due to the normal force F_N (see figure 6) the spring bow forces for the particular bows can be expressed as

$$\begin{aligned} F_{B1} &= (S_B - e) \cdot C_f \\ F_{B2} &= (S_B - d) \cdot C_f \\ F_{B3} &= (S_B - e) \cdot C_f \\ F_{B4} &= (S_B + e) \cdot C_f \qquad (8.1\text{-}6) \\ F_{B5} &= (S_B + d) \cdot C_f \\ F_{B6} &= (S_B + e) \cdot C_f \end{aligned}$$

F_{B1-6} = spring bow force for bows 1 to 6
S_B = bow compression
d = deflection of centralizer in vertical direction
e = change in bow compression for bows 30 degrees inclined from horizontal plane
C_f = spring bow constant

According to equations 8.1-1 and 8.1-6 the total radial spring bow force of a deflected centralizer is

$$\begin{aligned} F_{B-total} &= \sum_{n=1}^{6} F_{Bn} = F_{B1} + F_{B2} + F_{B3} + \\ &\quad F_{B4} + F_{B5} + F_{B6} \\ F_{B-total} &= 2 \cdot (S_B - e) \cdot C_f + (S_B - d) \cdot \qquad (8.1\text{-}7) \\ &\quad C_f + 2 \cdot (S_B + e) \cdot C_f + (S_B + d) \cdot C_f \\ F_{B-total} &= 6 \cdot S_B \cdot C_f \end{aligned}$$

This is equal to the total radial spring force of a non-deflected centralizer (equation 8.1-5). Due to symmetry considerations, this is also true for centralizers with a bow number differing from the number in this example.

8.2 Torque Analysis

The resistance of a single pipe against rotation can be calculated as follows:

$$T_R = \mu \cdot F_N \cdot 0.5 \cdot D_{Pipe} \qquad (8.2-1)$$

T_R = rotational torque
μ = friction factor
F_N = normal force
D_{Pipe} = Pipe diameter

The accumulation of these torque values from the casing- or liner-shoe up to the rotary table results in a torque value for each particular connection in the string.

Table1 Input Parameters and their Influence on Standoff, Drag and Torque

Parameter	Standoff	Drag	Torque
Pipe size	⊗	⊗	⊗
Pipe weight	⊗	⊗	⊗
Mud weight	⊗	⊗	⊗
Cement weight	⊗	⊗	⊗
Actual hole size	⊗	⊗	
Friction factor		⊗	⊗
Inclination	⊗	⊗	⊗
Azimuth	⊗	⊗	⊗
Type of centralizer	⊗	⊗	
Restoring force	⊗		
Running force		⊗	
Starting force		⊗	
Centralizer spacing	⊗	(⊗)	

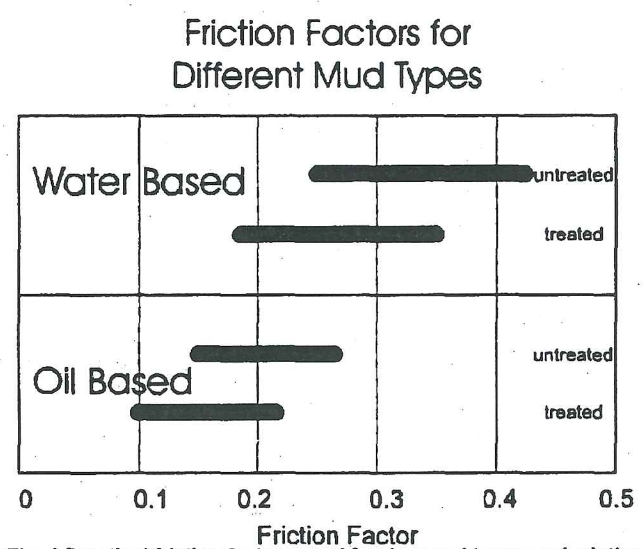

Fig. 1 Practical friction factors used for drag and torque calculation

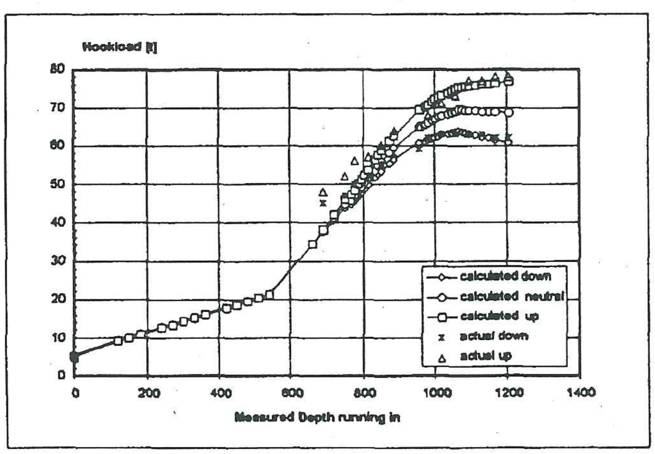

Fig. 2 Hookload diagram for a 7" horizontal liner (actual versus predicted)

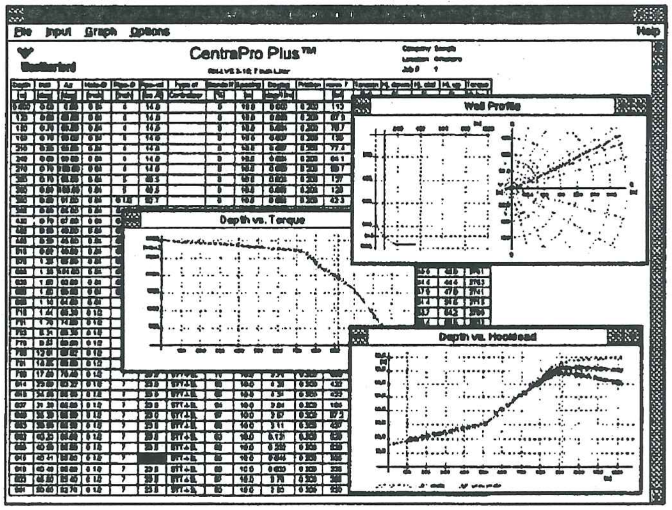

Fig. 3 Main screen of the computer program

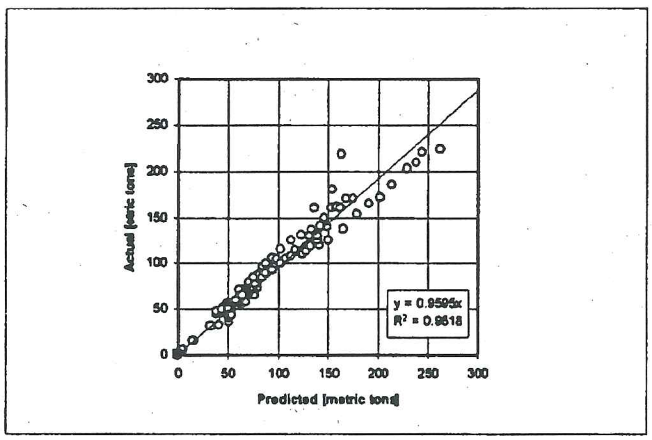

Fig. 4 Hookload, crossplot of predicted values versus actual values of several individual wells

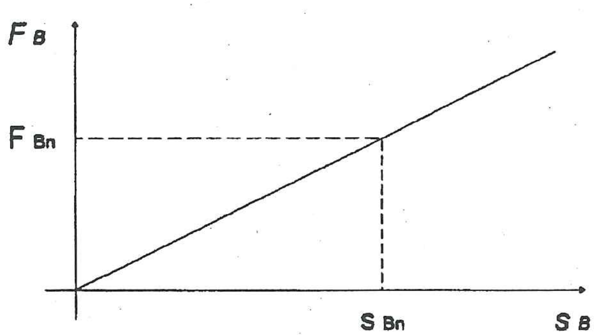

Fig. 5 Relationship between spring bow force and compression

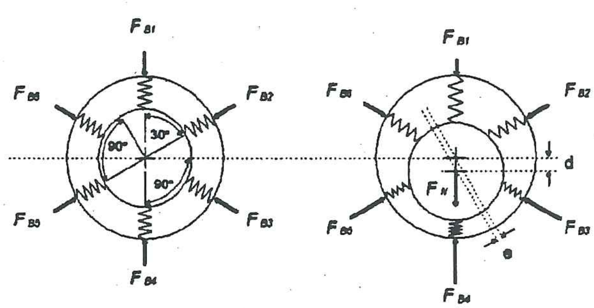

Fig. 6 Deflection of a centralizer with 6 bows