DIAGNOSTIC ANALYSIS OF DEVIATED ROD-PUMPED WELLS

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ABSTRACT

Diagnostic methods and programs for rod pumping commonly assume that the wellbore is vertical. Applying these methods to deviated wells will result in distortions and inaccuracies when calculating the down-hole pump card. This paper describes a new method for analyzing pumping efficiencies in deviated wells. The method requires a deviation survey for the **3-D** borehole trajectory that incorporates the dogleg effect (rod/tubing drag forces) into the solution of wave equation. The program is applicable to wells with bare rods, molded-on rod guides, and wheeled-rod guides or a combination of these. Real examples are shown to compare results from both programs. The deviated program improves the accuracy of the pump card and the card is easier to interpret. Thus, the producing pressure and pump displacement rate based on the pump card are more precise. In addition, the deviated diagnostic program can generate data that can be used to improve the accuracy of the deviated predictive program.

INTRODUCTION

Rod pumping has been widely used as a common artificial lift method. During the last four decades, the design and diagnosis of rod pumping installations have been based on the one-dimensional, viscous damped wave equation with the aid of computers and numerical techniques. It is accepted that the wave equation best describes the behavior of rod pumping systems and performs well in the diagnosis and design of rod pumped wells. A simple downhole friction law is incorporated into the wave equation. The viscous frictional forces along the rod string are assumed proportional to the rod velocity and act opposite to rod motion. In most vertical wells, the model can provide reasonable and correct results. Yet the model is imprecise and not valid for a crooked-hole, or deviated, well. Continued study on the mathematical modeling of crooked-hole rod pumping is imperative because these wells are becoming more and more common.

Crooked wells can be categorized into unintentionally deviated and intentionally deviated wells. No well in the world is perfectly vertical. Wells that were intended to be vertical can turn out to have certain doglegs that pose severe problems when using rod pumping equipment. Downhole friction between the rods and tubing can be excessive and cause severe rod-tubing wear and power losses.

Wells that are intentionally drilled along a trajectory deviate from the vertical to a predetermined target. Strong economic and environmental pressures have increased the use of deviated wells. Some wells are drilled horizontally to maximize hydrocarbon recovery from naturally fractured reservoirs. In some situations, there is no alternative but to drill a directional well. For example, oil production near natural obstructions such as mountains or other topographical features is made possible only by drilling a deviated well. A lake may be the only source of drinking water in the area, and thus there may be environmental restrictions that prohibit the use of drilling rigs and production facilities in or around the lake. When the well path is carefully planned and controlled, deviated wells thought to be infeasible with rod pumping equipment not long ago, can now be lifted. In most deviated wells, rod guides and tubing rotators are employed to minimize wear.

Most of the previous models for analysis and design of rod pumping installations presume a vertical well. Only a few viable models for dynamic behavior of deviated rod pumping system were published in the last decade. Lukasiewicz[1] developed a 2-D dynamic model for the rod string in an inclined well with consideration of the lateral effect of rods supported by numerous rod guides. Gibbs[2] in 1992 developed a 3-D mathematical model to include drag forces between the rod/rod guides and the tubing wall with the influence of the wellbore geometry. The 3-D crooked-hole model based on the modified version of wave equation was successfully incorporated into Lufkin Automation's rod pumping predictive and design software, called SROD. This feature has been of great benefit and used in oil fields worldwide for about eight years.

In 1998, Xu[3] presented a set of comprehensive mathematical models for predicting the behavior of rod pumping in both vertical and deviated wells. The model incorporated viscous fluid friction by computational fluid dynamics and Coulomb friction, or drag, with a combination of the effects of transverse deformation. In mid 2000, Lufkin Automation developed and released a new version of the rod pumping diagnostic software, DIAG, which uses a similar model and algorithm as SROD for diagnosing deviated wells. The model for deviated wells incorporates not only viscous friction, but also Coulomb friction (drag). This paper discusses the modeling technique and results using the crooked-hole version of the diagnostic software. Several examples are used to demonstrate that applying vertical diagnostic software to a deviated rod-pumped well would distort and cause misinterpretation of the downhole pump conditions and other downhole data such as pump intake pressure, tubing movement, pump leakage etc. The crooked-hole diagnostic model for the rod pumping system can provide more accurate and meaningful data for analyzing downhole equipment performance.

MATHEMATICAL MODEL

The governing equation that describes the dynamic behavior **of** the rod string in a vertical well is the 1-D wave equation. The wave equation is derived by a combination of Newton's second law for rod dynamics and Hooke's law of elasticity. The wave equation, used almost universally in rod pumping for a vertical well, is expressed as folows:

$$\frac{\partial^2 u(s,t)}{\partial t^2} = \nu^2 \frac{\partial^2 u(s,t)}{\partial s^2} - c\frac{\partial u(s,t)}{\partial t} + g \qquad (1)$$

where ν is wave propagation velocity in the sucker rod. c, represents the viscous damping coefficient which models the effects of fluid viscous friction. The viscous friction law in **Eq.** 1 assumes that friction forces along the rod are proportional to the velocity at each point in the rod string. In practice, the friction law can be used as an equivalent friction, the intention of which is to remove energy from the system in the same magnitude as the real friction forces. However, part of the friction is Coulomb friction, which is not velocity-dependent.

The friction law in Eq. 1 mimics the viscous fluid friction fairly well and its accuracy normally meets engineering acceptance. In vertical or near vertical wells, so-called equivalent friction is still valid because the rod-tubing drag forces are relatively small. However, in a non-vertical well, substantial rod-tubing drag forces occur. The Coulomb friction is independent of rod velocity and is proportional to the contact force between the rod and tubing, commonly referred to as side load. The equivalent friction model fails to represent this type of friction correctly. Thus, the calculated pump card would be distorted in wells with abnormal amounts of Coulomb friction. In addition, the side loads are also used to select the number of rod guides needed and the proper placement of the guides in the rod string.

According to the definition of Coulomb friction, rod-tubing or rod guide-tubing friction takes the form

$$F_r(s,t) \le \delta\,\mu(s)\,q_n(s,t) \qquad (2)$$

in which

F_r is rod-tubing drag force;

$\delta = \dfrac{\partial u(s,t)/\partial t}{\left|\partial u(s,t)/\partial t\right|}$, is an alternator ($\pm 1$) which makes drag friction act opposite to rod motion;

$\mu(s)$ is the coefficient of friction between the tubing and rods (or rod guides);

$q_n(s,t)$ is the side or normal forces at points where the rods or rod guides contact the tubing;

when the rod is in motion, use the = sign, and when the rod is in stationary, use the < sign.

The wellbore trajectory of a deviated well is a 3-D curve. An element of the rod as **a** free-body diagram in a deviated well is shown in Figure 1. The axial forces and drag forces on the rod element act along the tangent direction, side forces act normal to the rod axis, and rod weight acts in a downward direction. As in the vertical well version of the wave equation, Newton's law is applied to the rod in a deviated well with a combination of Hooke's law, viscous friction law and Coulomb friction law. Thus, the crooked-hole version of the wave equation is obtained as follows:

$$\frac{\partial^2 u(s,t)}{\partial t^2} = v^2 \frac{\partial^2 u(s,t)}{\partial s^2} - c\frac{\partial u(s,t)}{\partial t} - \delta\ \mu(s)[Q(s) + T(s)\frac{\partial u(s,t)}{\partial s}] + g(s) \quad (3)$$

where s is the measured depth starting from the surface; $Q(s)$ and $T(s)$ are functions which depend on axial load and wellbore deviation; $\mu(s)$ is the friction coefficient function which provides for variation of friction coefficient along the rod string (due to bare rods and different types of rod guides); and g(s) is rod weight effect. In the vertical well case, g(s) = constant, $Q(s) = T(s) = 0$, and hence Eq. 3 reduces to Eq. 1. In regions where the wellbore is straight but inclined, $T(s) \approx 0$, wherein the side load is not dependent on the axial load. The reader is referred to the literature? for a derivation of the functions $Q(s)$ and $T(s)$. The literature' also presents a model in which the friction coefficient, μ, is inferred from traveling- and standing-valve checks.

Eq. 3 is solved with the finite difference method subject to the boundary conditions for the pump, surface unit and prime mover. The algorithm is similar to that used in Lufkin Automation's predictive software, SROD. The recently released crooked-hole version of DIAG now solves the same equation to analyze the downhole pump conditions in a deviated rod-pumped well. However, the boundary conditions in the diagnostic analysis are different from those for the predictive analysis. This paper focuses on the diagnostic problem. In the diagnostic case, the boundary conditions are specified by the following equation

$$\begin{aligned} EA\frac{\partial u(s,t)}{\partial s}\Big|_{s=0} &= \mathit{measured\ polished\ rod\ load\ at\ surface} \\ u(s,t)\Big|_{s=0} &= \mathit{measured\ polished\ rod\ position\ at\ surface} \end{aligned} \quad (4)$$

APPLICATION TO DIAGNOSTIC ANALYSIS

Model Validation. It is difficult and costly to directly measure a downhole pump card in a deviated well using a downhole dynamometer. As a partial validation for the model and its algorithm, both SROD and DIAG were run for the same well and their respective downhole pump cards were overlaid for comparison. This example 9900 ft well has an API 86 steel rod design. The unit is operating at 5.5 SPM with a surface stroke of 120.4 inches. Figures 2 thru 4 show the wellbore path for the subject well. First, SROD was run to create a surface dynamometer card and pump card, then the predicted surface card was used to generate a downhole pump card with DIAG. The calculated pump cards are overlaid and shown in Figure 5. As shown, the predicted downhole pump dynamometer card matches the diagnostic downhole pump card exactly.

Deviated/Vertical Well Model Comparison. An example is used to demonstrate the difference between the deviated model and the vertical model. A 6020 ft well was selected. The unit is operating at **12.1** SPM with a measured surface stroke of 144 inches. Deviated DIAG requires a deviation survey to determine the location and magnitude of side forces and drag forces on the rods. Figure 6 presents a 3-D plot of the borehole path for the subject well. The borehole path is displayed as seen by looking in a northeast direction. Visualization of the wellbore path helps the analyst better understand where the rod guides are required to withstand the side forces. The 3-D view can be rotated on the vertical and horizontal axis to enhance 3-D visualization.

A surface dynamometer card, shown in Figure 7, was measured on this deviated well. Figure 8 shows the downhole pump cards computed by both vertical DIAG and deviated DIAG. The load range displayed at the pump with the conventional vertical model is much too large (13,580 Ibs). The load range at the pump computed with the deviated model is much less (10,421 Ibs). The vertical diagnostic model does not handle downhole friction along the rod appropriately. As shown, any forces along the rod string that are not properly modeled by the diagnostic equation will be erroneously transferred to the pump. Thus, the downhole pump card is distorted and inaccurate. The pump stroke computed by vertical DIAG (I 20 inches) is too long compared to the more precise pump stroke computed by deviated DIAG (I 12 inches).

These errors in load and stroke are serious and can cause misinterpretation of the downhole conditions. For example, if the fluid load were being read from the pump card to infer pump intake pressure, the vertical model would compute a producing pressure which is much too low. In the same sense, errors in load along the rod string would result in errors in rod loading. Also, inaccurate downhole pump cards will indicate more rod compression than actual. The minimum pump load computed with the vertical model is –3,742 lbs compared to the minimum pump load of -3,123 lbs computed with the deviated model. If rod buckling is a concern, this could lead one to excessively use sinker bars or rod guides to combat a buckling problem that may not exist. Ignorance of the true downhole friction forces also indicate a pump stroke that is larger than actual. Hence, the analyst might be led to search for a non-existent tubing leak or conclude that the well test is low. It is clear that calculated pump cards can be improved in deviated wells if the downhole friction can be properly modeled.

Inferring Coefficient of Friction. In both the predictive and diagnostic software, a coefficient of friction of 0.2 is set as a default value. Without support by field measurement or lab data, using a default value could be incorrect in some cases when designs based on a default value. Fortunately, an additional feature of crooked-hole DIAG is the ability to infer the correct coefficient of friction from measured surface traveling- and standing-valve checks. Also, owing to the shape of the downhole pump card, the proper coefficient of friction can be selected by eye. To illustrate the importance of the proper coefficient of friction, a well is selected with the pump set at 5,475 feet. The unit is operating at 6.69 SPM with a surface stroke of 148 inches. Figures 9 thru 11 show East-West, North-South, and plan views of the wellbore path. Figure 12 shows a measured surface dynamometer card and a downhole pump card using both vertical DIAG and deviated DIAG. Obviously, the discrepancy between both models is significant. The load range at the pump computed from the vertical model is 4,878 lbs while the one from the deviated model is 3,260 lbs. The minimum pump load computed from the vertical model is –2,089 lbs while the one from the deviated model is –1,562 lbs. This erroneously indicates more buckling tendency with the vertical model. As discussed earlier, this difference is caused by not considering drag friction along the rod string in the vertical model.

Another experiment was made by using different coefficients of friction, i.e. , 0.2, 0.1, and 0.05 respectively. All corresponding calculated downhole pump cards are displayed in Figure 13. It was found that the default coefficient of friction of 0.2 results in a negative pump power which is incorrect. If a lower coefficient of friction of 0.1 is chosen, the downhole pump card still has an improper shape and pump power still is too low. By trial and error, the best coefficient of friction of 0.05 was selected because the calculated downhole pump card appears more reasonable. Thus, in this case a coefficient of friction of 0.05 should be used instead of the 0.2 default value.

Side forces, Drag Forces and Buckling Tendency. Like SROD, crooked-hole DIAG can analyze side forces, drag forces, and buckling tendency. Figure 14 shows axial load and buckling tendency versus measured depth. Buckling in rod pumping installations is caused by the pump hitting down, pump friction, fluid pound, and fast pumping speeds. Rod string buckling accelerates rod and tubing wear deep in the well (near the pump) and often results in tubing leaks. Figure 15 shows a plot of side forces on the rod string versus measured depth. Figure 16 shows a plot of drag forces between the rod and tubing versus measured depth. The diagrams of side forces and drag forces are used to evaluate what is occurring in an existing deviated well.

CONCLUSIONS

1. A modified version of the wave equation method has been developed which considers and quantifies rod/tubing side loads and drag for deviated wells.
2. Deviated SROD and deviated DIAG use similar mathematical models and the finite difference algorithm to improve the accuracy in both designing and diagnosing rod pumping systems.
3. When the effects of rod/tubing drag are ignored in a deviated well, the computed pump load range and pump stroke (pump displacement) are erroneously increased. Also, the pump card is distorted.
4. Reasonably accurate coefficients of friction can be determined from traveling- and standing-valve checks and from the shape of the computed downhole pump card.

NOMENCLATURE

A=cross sectional area of rod, ft^2
c=viscous damping coefficient, sec^{-1}
C(s)=function defining Coulomb friction effects, ft/sec^2
E=elastic modulus, lbf/ft^2
F= axial force, lbf
F_f=friction force, lbf

F_r=rod/tubing drag force, lbf
g=local acceleration of gravity, ft/sec^2
g(s)=component of acceleration of gravity, ft/sec^2
q_n(s,t)=side force, lbf
Q(s)=normal or side forces due to component weight of rod against tubing, ft/ sec^2
t=time, sec
T(s)=function defining effect of axial force on Coulomb friction, ft/sec^2
u(s,t)=position of rod, ftn=propagation velocity in rod, ft/sec
W=rod weight, lbf
δ =alternator ($\pm$ 1 depending on rod velocity)
μ(s)=coefficient of friction

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3. Xu, J., Doty, D.R., Blais R., and etc: "A Comprehensive Rod-Pumping Model and Its Application to Vertical and Deviated Wells," SPE paper 52215 presented at 1999 SPE Mid-Continent Operations Symposium held in Oklahoma City, OK, March 28-31.
4. Gibbs, S. G. and Neely, A. B.: "Computer Diagnosis of Down-Hole Conditions in Sucker-Rod Pumping Wells," *JPT* (January 1966) 91-98.
5. Xu, J., Shirazi, S.A. and Doty, D. R.: "Prediction of Turbulent Friction in Rod-Pumped Wells," SPE Journal Vol.5 no. 2, June 2000.
6. Gibbs, S. G.: "A General Method for Predicting Rod-Pumping System Performance," SPE paper 6850 presented at the 1977 SPE 52nd Annual Fall Technical Conference and Exhibition, AIME, Denver, Colorado, Oct.9-12.

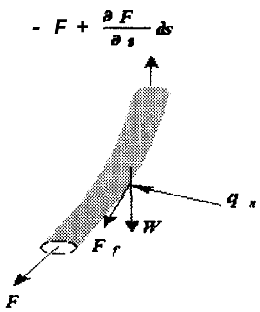

Figure 1 - Schematic of Rod Element in a Deviated Well

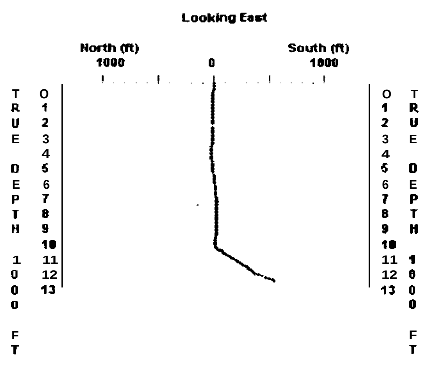

Figure 2 - East-West Borehole Path

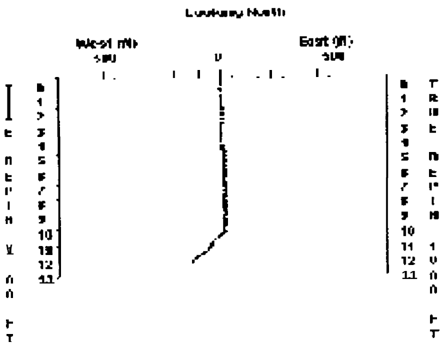

Figure 3 - North-South Borehole Path

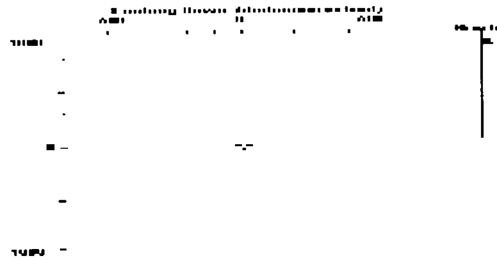

Figure 4 - Looking Down Borehole Path

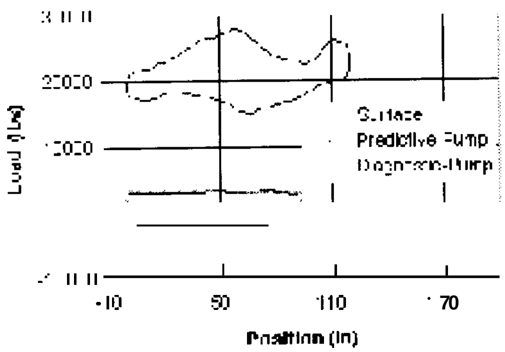

Figure 5 - Comparison of Downhole Pump Cards Calculated by SROD and DIAG

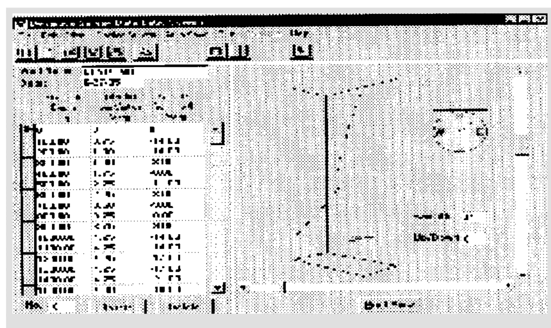

Figure 6 - 3-D Plot of the Borehole Path

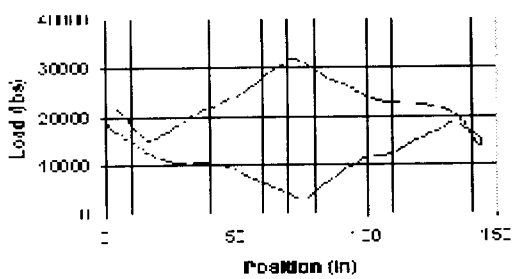

Figure 7 - Measure Surface Card

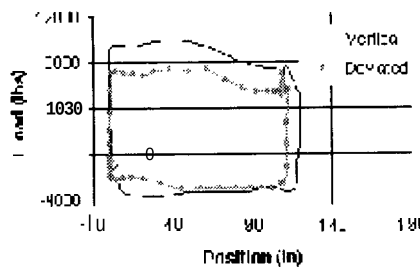

Figure 8 - Downhole Pump Cards Computed by the Vertical and Deviated Model

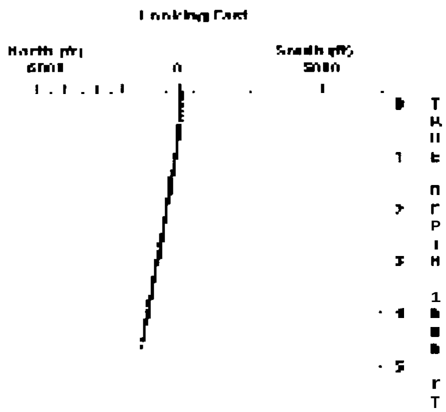

Figure 9 - East-West Borehole Path

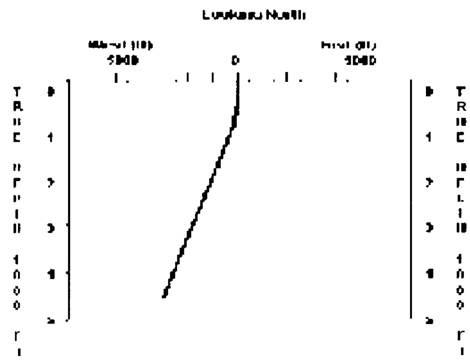

Figure 10 - North-South Borehole Path

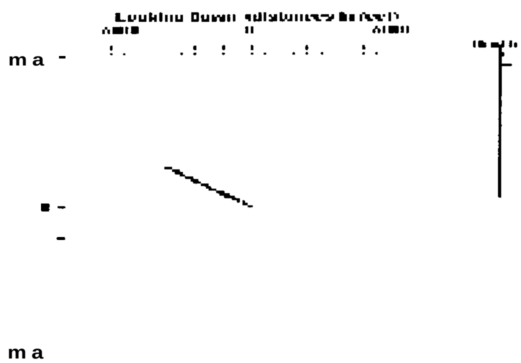

Figure 11 - Looking Down Boarehole Path

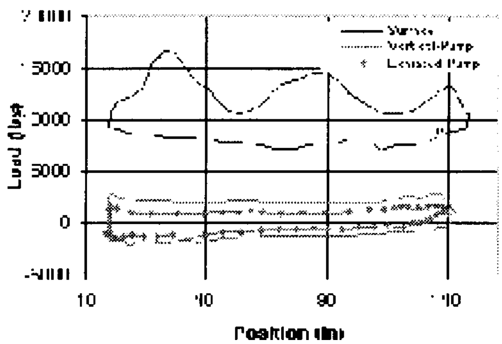

Figure 12 - Downhole Pump Cards Computed **by** the Vertical and Deviated Model

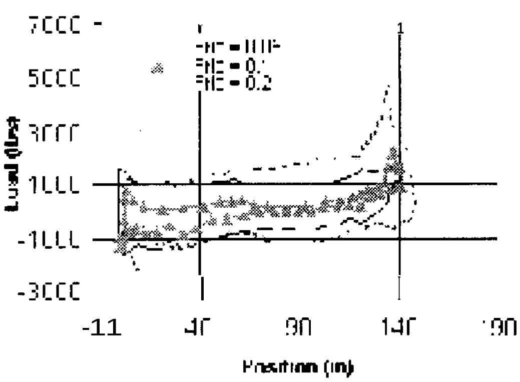

Figure 13 - Comparison of Downhole Pump Cards with Different Coefficients of Friction

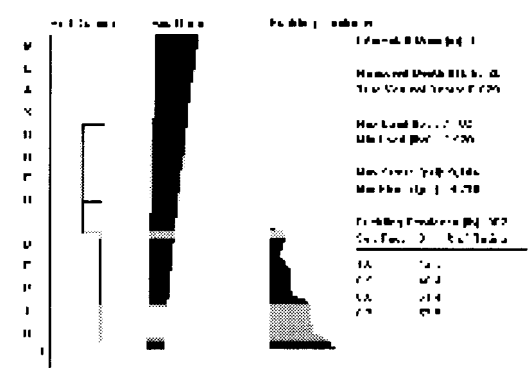

Figure **14** - Graphs of Axial Load and Buckling

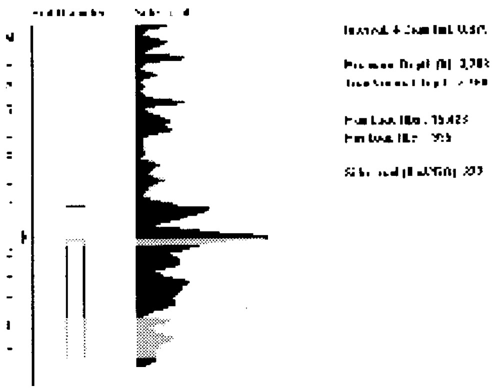

Figure 15 - Side Force Plot

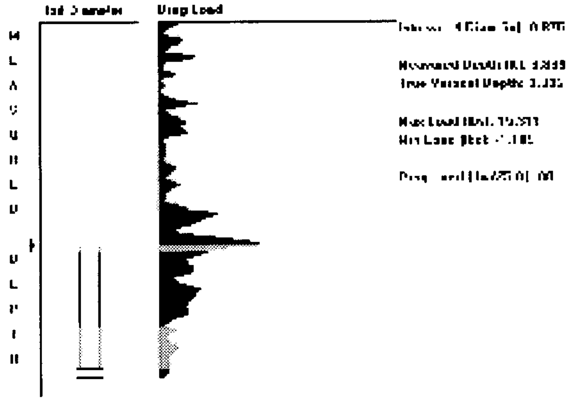

Figure 16 - Drag Force Plot