SUCKER ROD PUMPING SYSTEM DESIGN TOOLS FOR QROD

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ABSTRACT

QRod is the most widely used program for the design and prediction of the performance of Sucker Rod Beam Pumping Installations. A damped wave equation solution is used to accurately predict the surface dynamometer loads, gearbox torque and pump capacity, with a minimum amount of input with results shown is any system of units. New design tools have been added to include:

1) Slippage Calculator uses pump clearances to tie the pump efficiency to the predicted pump displacement.
2) Sinker Bar length calculator determines the sinker bar length as pump diameter or pump depth changes.
3) Tubing Fluid specific gravity calculator.
4) Dynamometer measured surface DYN files can be imported and plotted on top of the predicted dynamometer card.

QRod's objective is to help the beam pumping system designer implement state of the art design technology without getting buried with details. Changing a parameter such as tubing anchor, stroke length, stroke rate, or pump diameter is immediately seen in the dynamically updated plots.

INTRODUCTION

ORod[1] is a beam pumping simulator or is classified as a predictive sucker rod design program. QRod mathematically simulates the kinematic polished rod motion for a given stroke length of a particular type of surface pumping unit to define the boundary condition at the surface. The fluid load that the pump applies to the bottom of rod string is used to set the other boundary condition at the bottom of the rod string, based on the expected pump intake pressure, specified plunger size, vertical pump depth, tubing pressure, and tubing fluid gradient. Using the pump load and polished rod motion QRod then solves the partial differential wave equation describing the motion of the rod string to predict the surfaces loads and corresponding plunger velocity and position. For the particular type of pumping unit the gear box torque and required counter balance are determined using the predicted surface dynamometer card's surface loads and polished rod position.

For the beam pumping system, once a depth and desired pumping rate are known, the primary design variables are stroke length, plunger diameter and pumping speed (SPM). These are three variables that are usually adjusted to achieve the desired optimized design. The design objective may be to minimize power required or minimize rod loading or just calculate the pump displacement. Secondary design variables may be adjusted to fit the particular situation or to achieve a better match to a measured surface dynamometer card. QRod has number of secondary design variables including Unit Type, API Rod String Number or Grade, Pump Intake Pressure, Fluid Specific Gravity, Tubing Pressure, and Damping Factor. The primary objective of the QRod program is to achieve an accurate of solution with a minimum of supplied input data to simulate the rod pumping system.

Throughout a complete stroke the predicted surface dynamometer card of rod loads in default units of pounds is plotted at the various position of the upstroke and down stroke in default units of inches; but other display units such as kg for load and cm, mm for position can be selected. The pump dynamometer card is plotted in the same window and with the same units as the surface dynamometer card; the pump card represents the fluid load the pump applies to the bottom of the rod string at the various positions throughout the stroke. The full pump card with anchored or unanchored tubing is used for the boundary condition at the pump; the pump is filled with liquid with no gas in the pump, the valves are not leaking, and the pump is functioning properly. Incomplete pump fillage is not an option for predictions using QRod.

The objective of QRod is to help the beam pumping system designer implement state of the art design technology without getting buried with details. QRod results obtained include loads, stresses, torques, power, and pump displacement. The impact of changing a parameter such as tubing anchor, stroke length, stroke rate, and pump diameter can be immediately seen in the dynamically updated plots. The output of the QRod program includes the net pump displacement, rod string loading, percentage of rod lengths making up the rod string taper, minimum API size of surface pumping unit and NEMA D motor size requirements for any input depth and design production rate. QRod is an accurate sucker rod design program, having all of the features required to design the sucker rod pumping installation, but without complicating features which tend to add very little to the accuracy but much to the complexity of the use of the software.

QRod's tapered rod string design results in the largest diameter rods are located at the top of the string. These rods support the weight of the all the rods connecting the pump to the top rod in each taper. The rod loading at the top rod in each taper are the highest. The rod loading decreases as the suspended rod weight decreases as you move closer to the pump. **Table1** defines the API rod number used to specify the rods making up a tapered steel rod string. The API rod number for the steel rod string is selected from this list shown in **Table 1**. The API rod number is in 1/8 of an inch, so a 1inch diameter rod is called 8. An API rod number of 86 means, the rod string is composed of 8/8", 7/8", and 6/8" diameter rods. 76 rods have been selected as the initial default rod taper for a design. The percentage of each size is determined by the API method and depends on the pump diameter. This method will result in approximately equal stresses at the top of each rod section, which is referred to as a balanced design. The rod string is designed for a long operational life; the planned failure mode should be due to fatigue and the operator's objective is to wear the rod string out. A mixed string of fiberglass and steel rods also can be designed.

Four new calculators have been added to QRod, these imbedded calculators can be activated so that the output from the calculator is used as part of the prediction. The **Pump Slippage Calculator** allows the pump clearance to be specified and the resultant pump efficiency based on the design conditions to be used to calculate the pump slippage, pump efficiency and to predict the net pump displacement. The **Sinker Bar Calculator** is used to determine the length of the sinker bar section at the bottom of the rod string, and automatically adjusts the required sinker bar length as the tubing fluid gradient, pump diameter or pump depth changes. A **Tubing Fluid Specific Gravity Calculator** provides a simple process for the sucker rod designer to calculate a gas free tubing fluid gradient based on oil and water gravity, plus water cut. Once the surface dynamometer card is predicted by QRod, then a **DYN File Import** reads a file containing measured surface dynamometer card load and position data and then overlays the measured and predicted surface cards; comparing peak load, minimum load, polished rod stroke and horsepower. The measured and predicted dynamometer cards are compared by plotting the predicted card on top of the measured dynamometer card. These four calculator QRod tools will be discussed in more detail in the following sections.

Pump Slippage Background

Pump slippage[2,3,4,5] is the liquid that slips between the plunger outside diameter and the pump barrel inside diameter into the pump chamber between the standing valve and traveling valve when the traveling ball is on seat. A slippage formula **Eq. 1** called the Patterson equation is available to calculate the slippage volume and used to determine impact of slippage on pump efficiency and pump production.

$$Slippage = [(0.14 \cdot SPM) + 1] 453 \frac{DPC^{1.52}}{L\mu} \qquad \textbf{Eq. 1}$$

Pump slippage increases with increasing pump speed. Pump displacement increases faster than pump slippage resulting in greater pump efficiency with increasing speed. Proper selection of pump clearances is important in sucker rod pump design. If well configuration and well conditions are ignored in the selecting of pump clearances, then slippage rates may be larger than expected and pump efficiencies may be too low.

In the SWPSC 2007 paper[2] **Eq. 1** was presented as being the best predictive tool for rod pump slippage. By unanimous consent of all test participants, it is agreed that **Eq. 1** should henceforth be referred to as the "Patterson Equation" in honor of John C. Patterson who has spearheaded the effort since the inception of slippage research beginning in 1996.

When Does Pump Slippage Occur

Sucker rod pumps typically consist of a plunger/traveling valve assembly connected to the rod string and barrel/standing valve assembly attached to the tubing. The traveling valve is considered to be the discharge valve and moves with the rod string. The closed traveling valve acts as a check valve to keep well fluid in the tubing on the upstroke. Standing valve acts as the intake valve, fixed to tubing, and acts as a check valve to keep well fluid in the tubing on the downstroke. The outside diameter of the plunger is less than the inside diameter of the barrel. This difference in diameter is called pump clearance and is usually expressed in thousands of an inch. When the traveling valve is open the fluid in the pump barrel is displaced into the tubing by the plunger moving into the pump barrel on the downstroke.

Figure 1 is a pump card representing the load the pump applies to the rod string. On the pump card the standing valve is closed from C-D, D-A, and A-B; and the standing valve is only open from B-C. Before the beginning of the upstroke the pressure from the tubing fluid is applied to the closed standing valve and the traveling valve is open as fluid is displaced from inside the pump into the tubing (D-A). At the start of the upstroke, A, the traveling valve and standing valve are both closed and the pressures above and below the plunger are equal. During the upstroke (A-B-C-D) the fluid load applied to the rod string is due to differential pressure acting on the plunger and is equal to the pump discharge pressure minus the pump intake pressure times the area of the pump plunger. The fluid load is gradually transferred from the tubing (A-B) as the rods stretch to pick up the fluid load. The standing valve opens at B when the pressure in the pump drops below the pump intake pressure, allowing fluid to enter the pump chamber. From point B to C, the rods carry the fluid load while well fluids are drawn into the pump. At C, the standing valve closes, and the traveling valve remains closed until the pressure inside the pump is slightly greater than the pump discharge pressure. From C to D, gas in the pump (if present) is compressed as the plunger moves down to increase pressure on the fluid from the intake pressure to the static pressure in the tubing. As the fluid in the pump barrel is compressed, then the fluid load is gradually transferred from the rods to the tubing. At D, the pump barrel pressure equals the static tubing pressure, and the traveling valve opens.

Pump slippage can only occur when the traveling ball is on the seat during the stroke from A-B and B-C and C-D. Slippage through the pump clearances can only occur when the traveling valve ball is on the seat and differential pressure is acting across the plunger. Slippage is the liquid that slips between the plunger outside diameter and the pump barrel inside diameter into the pump chamber between the standing valve and traveling valve when the traveling ball is on the seat. Normally for a well that produces water, the liquid that slips back into the pump is usually water because the lighter oil and gas slip away from the top of the plunger on the upstroke and only the heavier water tends to remain on the top of the plunger. Liquid slippage into the pump barrel on the upstroke fills a portion of the pump chamber with liquids from the tubing and results in less well fluids entering the pump chamber, so the result is reduced pump displacement.

What is a Reasonable Amount of Pump Slippage

The normal recommended amount of pump slippage is from 2 to 5 percent of a sucker rod pump's displacement. For the purposes of lubrication 2 to 5 percent slippage of the pump's down hole displacement is considered to be sufficient. It is recognized that if the pump displacement rate is low (small pump for instance) and the percent slippage is high, it is possible to increase SPM to account for slippage but for larger rates and larger pumps, extra SPM creates significant extra loads and loss of energy. Pump Slippage % is defined as the percentage of slippage in BPD compared to the total pump displacement BPD and is shown in **Eq. 2**.

$$PumpSlippage\% = \frac{SlippageRate}{PumpDisplacment} \times 100 \qquad \textbf{Eq. 2}$$

Pump Efficiency % is defined by **Eq. 3**.

$$PumpEfficiency\% = \frac{SurfaceRate}{PumpDisplacment} \times 100 \qquad \textbf{Eq. 3}$$

The slippage percentage gets less (pump leaks less) as the pumping speed, SPM, is increased. When a pump is worn out and the production rate from the well has dropped off and the pump needs to be pulled and replaced with new;

then increasing the pumping speed of a leaky worn pump will increase pump efficiency and likely increase liquid produced to the surface. The operator should recognize that pump efficiency increases with increased SPM. Although increasing the pumping speed from 6 SPM to 10 SPM reduces pump slippage by only 5-6% and may result is a temporary increase in the production rate, the higher pumping speed can also result in increased failures and the temporary increase in oil production make not pay off any damage caused by a failure due to pumping too fast.

Pump Slippage Calculator

The recommended procedure to select pump clearances is to first use the predictive program QRod to calculate pump displacement, BPD, assuming 100% liquid fillage. **Fig. 2** shows the resulting no slippage pump displacement of 183.5 BPD calculated using QRod with data input to match the configuration of the TTU test well during the 08/25/06 18:24:56 slippage test with a 0.005 pump clearance, the 76 API rod string taper, and 7.045 SPM. **Fig. 3** slippage calculator inputs are displayed after clicking the calculator button next to the "Pump Volumetric Efficiency" text. **Fig. 4** plots the slippage volume in BPD versus pump clearances ranging from 0.003 to 0.012. A Pump clearance of 0.005 calculates a pump slippage of 18.64 BPD, which is slippage % of approximately 10% of the QRod predicted pump displacement. A tighter pump clearance of 0.003 inch would result in 5% slippage resulting in sufficient slippage to lubricate the barrel, but this for this example the 0.005 inch clearance is used to compare the calculated slippage of 18.64 BPD to the measured slippage of 21.4 BPD during this particular TTU slippage test. The pump volumetric efficiency is approximately 90% with this 0.005 inch clearance pump, with a measured 159 BPD produced into the tank while QRod predicted pump displacement reduced for slippage would 165 BPD. **Fig. 5** displays the **Dyn File Import** measured versus QRod predicted surface and pump cards from the TTU slippage testing 08/25/06 18:24:56 for stroke #36. The dyn file import and overlay show that the predicted QRod peak polished rod load of 11,223 lbs is within 1.7% on the peak load of 11414 lbs measured during the slippage test.

Pump Clearances should be specified by the operator to the pump shop. The above recommended "Procedure to Select Pump Clearances" should be followed or the pump that is installed in a well may be inefficient due to too open clearances and too much slippage. The Patterson equation is available to calculate the pump slippage volume and should be used to determine impact of slippage on pump efficiency and pump production. Pump slippage increases with increasing pump speed. Pump displacement increases faster than pump slippage resulting in greater pump efficiency with increasing speed. Proper selection of pump clearances is important in sucker rod pump design. Pump slippage may be excessive for large clearance pumps when pumping from deeper depths with high temperatures. System efficiency can be significantly reduced at slow SPMs with "large" pump clearance. Following are the steps to select correct pump clearances:

1. Use predictive sucker rod design program to calculate pump displacement, assume 100% liquid pump fillage.
2. Input correct well parameters, be sure to adjust water viscosity for the temperature at the pump
3. Examine "Pump Slippage Plot" and select pump clearance that gives the desired percentage of pump slippage.

Tubing Fluid Specific Gravity Calculator

It is common to describe the tubing fluid gradient in terms of psi/ft as a gradient or in terms of specific gravity where the tubing fluid is compared to pure water as a ratio of densities. This calculator is a tool that simplifies the calculation of the tubing fluid gradient and simplifies converting the tubing fluid gradient to the proper system of units required as data input into the QRod program. The use of this calculator will speed input and help define a critical variable used in the sucker rod design. The tubing fluid specific gravity is used in the calculation of the sinker bar lengths, calculation of weight of sucker rods in fluid, pump discharge pressure, and the fluid load the pump applies to the bottom of the rod string. **Fig. 6** shows the **Tubing Fluid Specific Gravity Calculator Tool** with the units "Sp.Gr.H2O" for Water Specific Gravity highlighted and displays a list of all other possible units that can be selected for the display of the tubing fluid gradient. This calculator makes the QRod program easier to use any location in the world by not restricting the input of the tubing fluid gradient input to one specific system of units.

Sinker Bar Calculator

The **Sinker Bar Calculator** is used to determine the length of the sinker bar section at the bottom of the rod string, and automatically adjusts the required sinker bar length as the tubing fluid gradient, pump diameter or pump depth changes during the interactive design process. **Fig. 7** shows the input data determining the required sinker bar length of 150 feet of sinker bars for the 3,896 foot pump depth and 1 Sp.GR. tubing fluid specific gravity for the TTU test well with a plunger size of 1.5 inch diameter. When the Use Calculation button is clicked on the Sinker Bar Calculator input screen, then a green check mark on the calculator icon on the main QRod screen shows that the automatic mode is selected. When the green check mark is displayed the sinker bar length and weight automatically are re-calculated as the QRod design progresses and any of the Sinker Bar Calculator inputs are changed.

Use of sinker bars in rod pumped wells is proven to reduce failures[7]. During a 10 year time period the failure frequency was reduced from 2.73 to 0.42 failures per well per year. In the paper[7] one of the best practices that contributed to the reduction in failures was "Installation of an average of 375' of 1.5" Grade-C Sinkerbars to reduce buckling during the downstroke."

QRod uses a very simple method of calculating the required sinker bar weight based on a sinker bar factor for the plunger diameter. The required weight is then used to calculate the length to the next largest length in multiples of 25 foot sections. To determine the sinker bar length, the sinker bar factor used in QRod is a continuous function and a sinker bar factor **Fig. 8** can be calculated for any size plunger. **Fig. 8** is a plot of previously published Sinker Bar factors that are based on the seat area of a sucker rod valve cross-sectional area. Notice at largest plunger sizes QRod uses a much lower sinker bar factor, than the published value. The sinker bar factor concept was based on the idea that the ball and seat sealed over the entire surface area of the seat and a differential pressure acted across the seat. A specific weight of sinker bars is required to overcome a compressive force that was created over the seat seal area. The problem with this concept is the ball and seat have a line seal and very little pressure is required to open the valve and no compressive buckling force can be created if there is no area for the pressure to act upon. So the sinker bar factor concept to calculate a compressive buckling force is invalid. Field experience[8] has shown a 93% reduction in tubing leaks and a 65% reduction in rod failure and this failure reduction have been attributed to the use of sinker bars; so sinker bars have been proven to be effective in reducing failures in sucker rod lifted wells. The sinker bar factor used by QRod should be considered an experience factor. For deeper well, larger diameter plungers, and heavier gravity oil more sinker bar weight is required to prevent excessive rod and tubing failures. Since the 1980 this sinker bar design technique programmed in QRod has been continually used throughout the United States to determine sinker bar length. The length of sinker bars that QRod calculates has been proven by field experience to reduce tubing and rod failures.

SUMMARY AND CONCLUSIONS

QRod[6] is a program that obtains a solution to the damped wave equation describing the motion of sucker rod pump strings. It uses an approximation for the motion of the surface unit as the surface boundary condition. The results obtained include loads, stresses, torques, power, and pump displacement. The new calculator tools have enhanced the functionality of the QRod design process. QRod can be used to design a new sucker rod installation. QRod can be used to predict expected loadings and compare to measured loadings. QRod should be used if a change in the operation of a sucker rod installation is contemplated, and quick prediction from QRod can be used to understand the impacts of the change on the equipment installed on the well.

QRod is the most widely used, free program for the design and prediction of the performance of Sucker Rod Beam Pumping Installations. Options are available for selecting the output and input language of either English or Spanish. QRod is available as a software program for installation on a PC or a simple Web based calculator. QRod can be used as a simplified online calculator via the Echometer web page, http://www.echometer.net/QRod/. The software can be downloaded for installation and use on any numbers of PCs from http://www.echometer.com/software/index.html .

Nomenclature:

D = nominal diameter, inches
C = diametrical clearance, inches
P = Pressure drop across the plunger, psi
L = length of the plunger, inches for Patterson, feet for the theoretical approach
SPM = strokes per minute
μ =viscosity of fluids, cp

REFERENCES

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Table 1 – API Rod Number

mm =>	32	29	25	22	19	16	
API Rod Number	1 1/4"	1 1/8"	1"	7/8"	3/4"	5/8"	
55						✓	All 5/8"
65					✓	✓	Top 3/4" with 5/8" on bottom
66					✓		All 3/4"
75				✓	✓	✓	Top 7/8" with 3/4" in Middle and 5/8" on bottom
76				✓	✓		Top 7/8" with 3/4" on bottom
77				✓			All 7/8"
86			✓	✓	✓		Top 1" with 7/8" in Middle and 3/4" on bottom
87			✓	✓			Top 1" with 7/8" on bottom
88			✓				All 1"
97		✓	✓	✓			Top 1 1/8" with 1" in Middle and 7/8" on bottom
98		✓	✓				Top 1 1/8" with 1" on bottom
99		✓					All 1 1/8"
108	✓	✓	✓				Top 1 1/4" with 1 1/8" in Middle and 1" on bottom
109	✓	✓					Top 1 1/4" with 1 1/8" on bottom

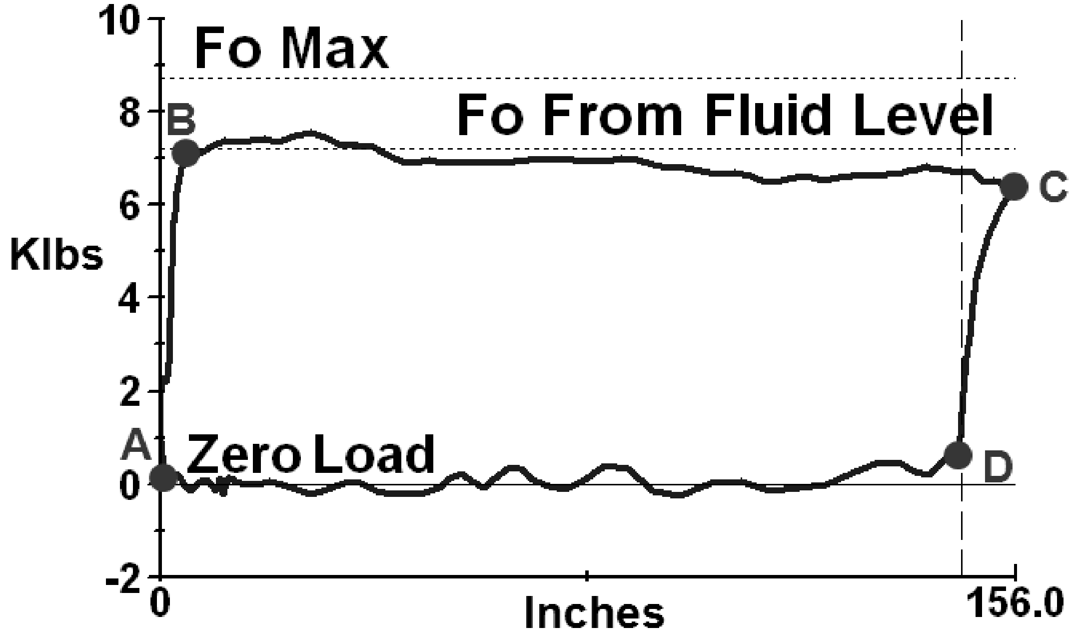

Figure 1 – Typical Pump Card with Point ABCD Labels Showing Where Valves Open or Close

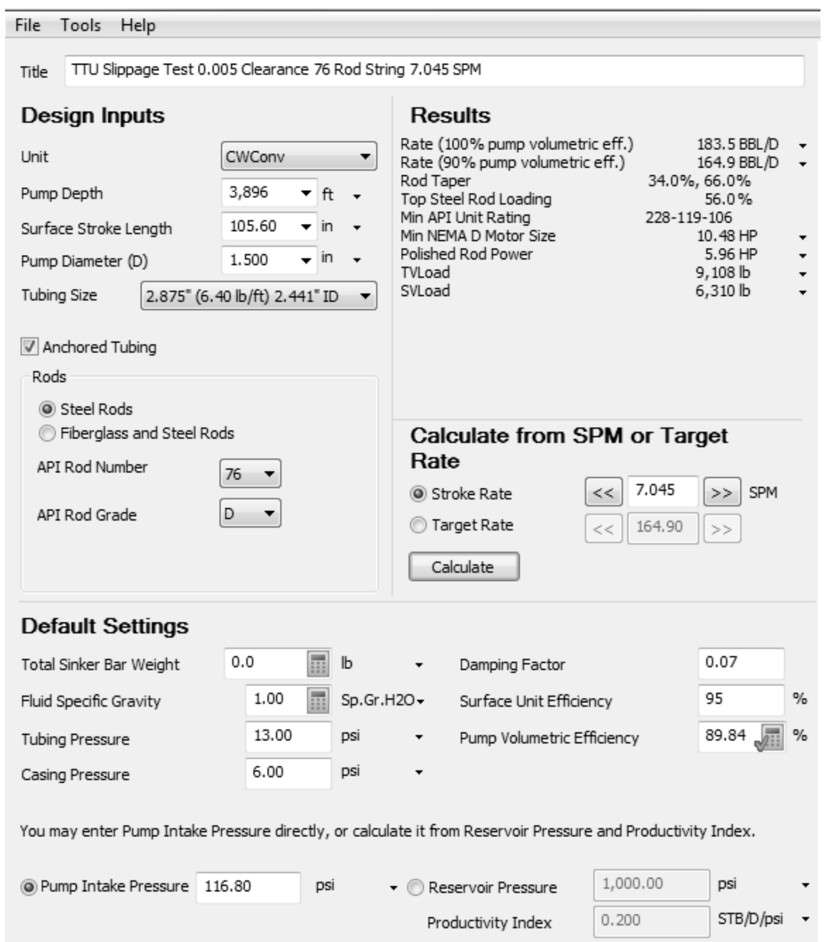

Figure 2 – Resulting Pump Displacement Calculated using QRod - TTU Slippage Test 0.005 Clearance 76 Rod String 7.045 SPM

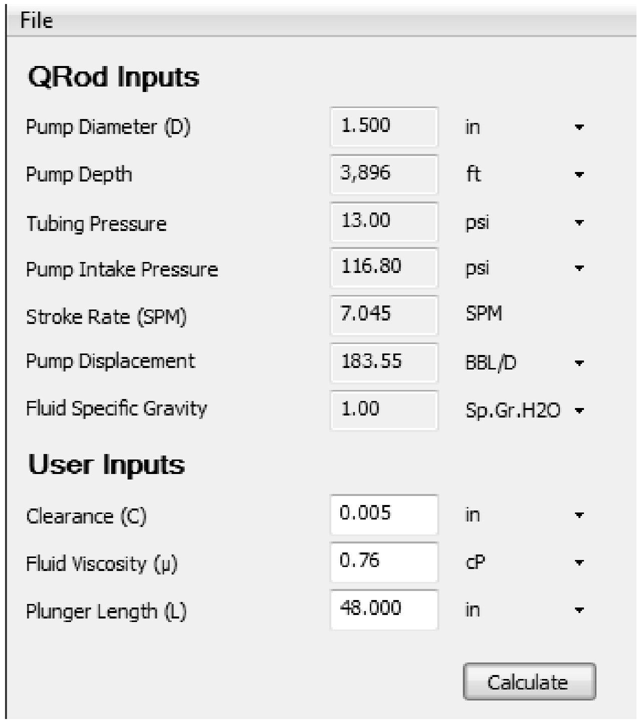

Figure 3 – Pump Slippage Calculator Inputs

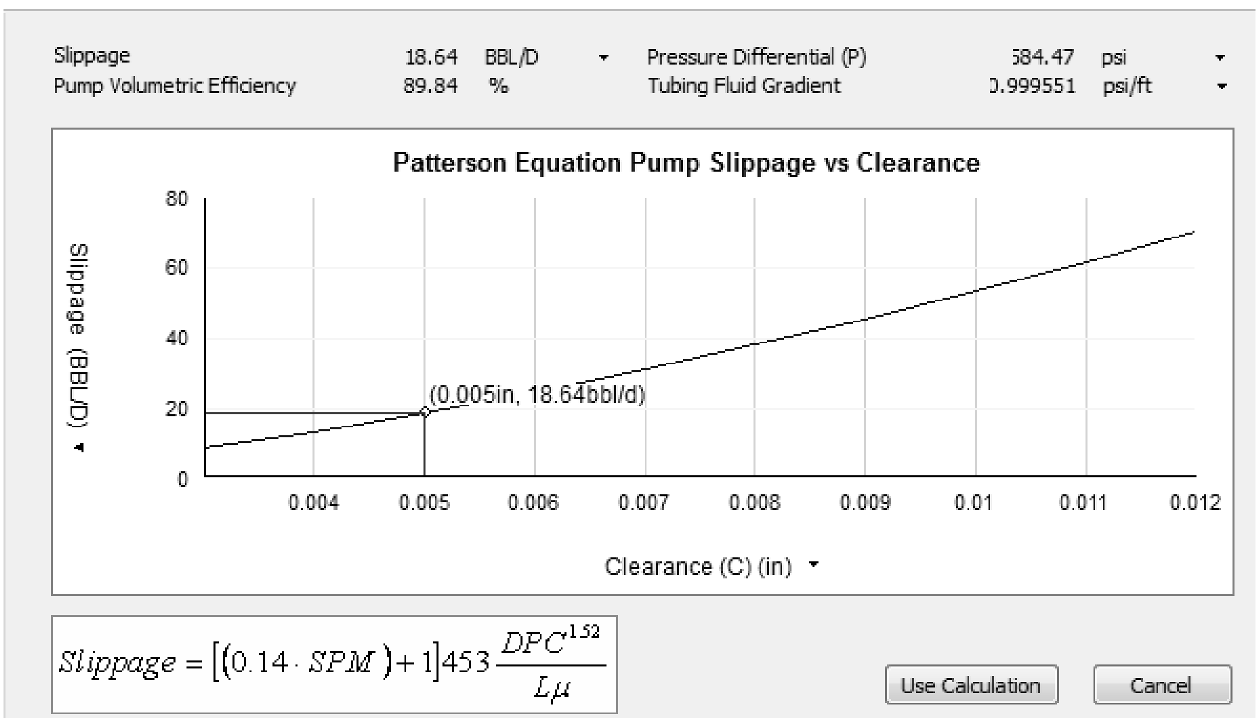

Figure 4 – Pump Slippage (BPD) versus Pump Clearances Ranging from 0.003 to 0.012

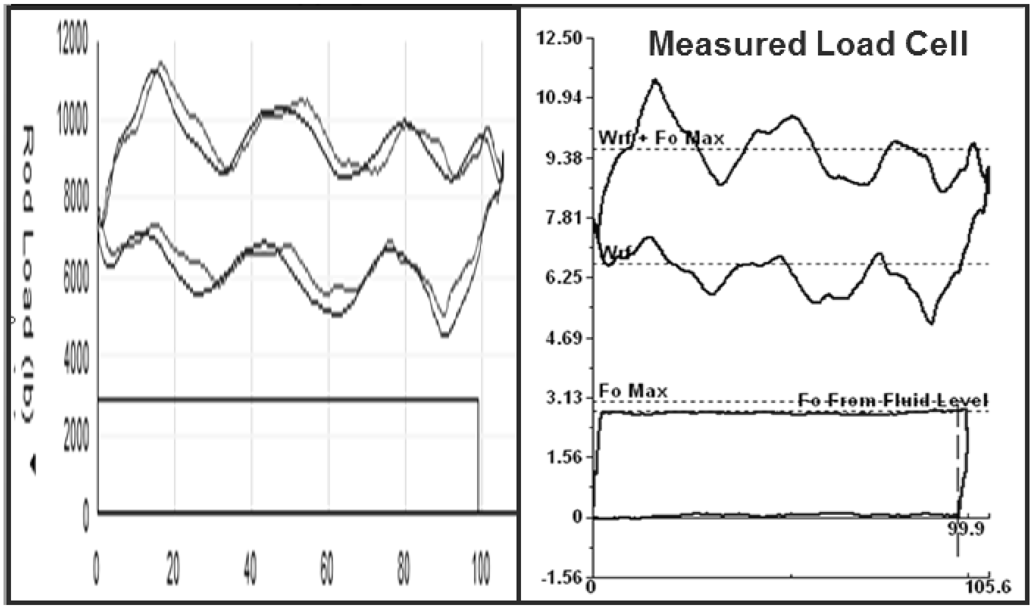

Figure 5 – Measured vs Predicted Surface and Pump Card from TTU Slippage Test: Stroke #36 08/25/06 18:24:56

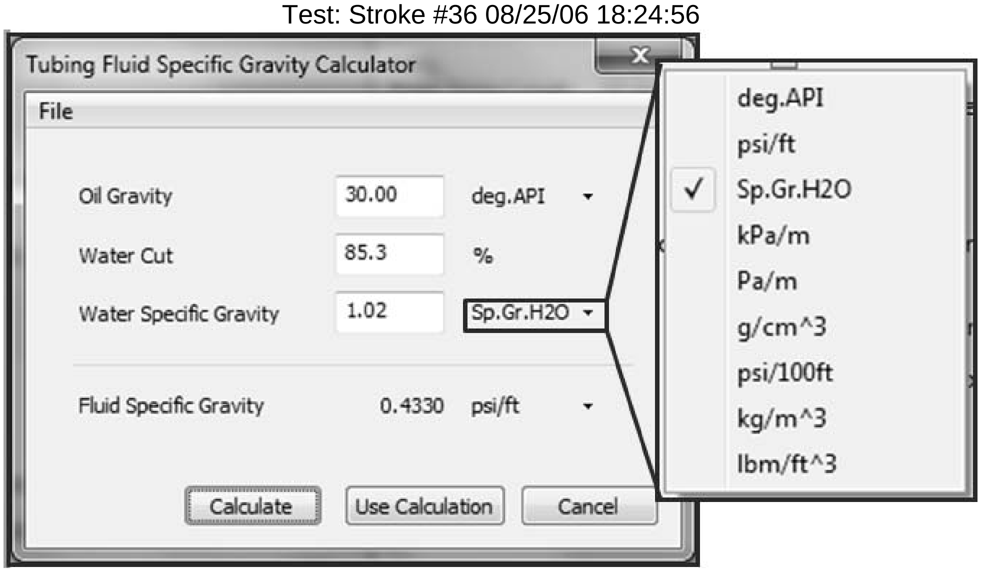

Figure 6 – Tubing Fluid Specific Gravity Calculator

Figure 7 – Sinker Bar Calculator

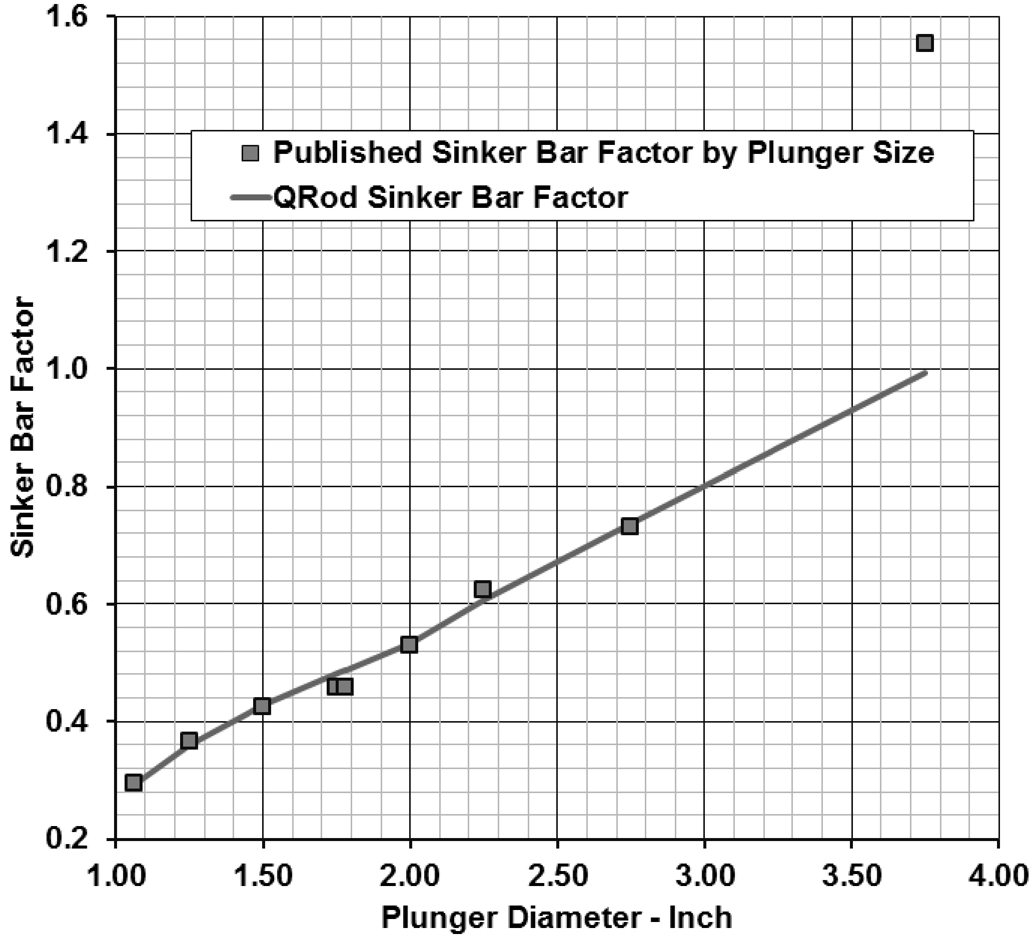

Figure 8 – Sinker Bar Factor