**A proposal for the real-time measurement of drill bit tooth wear**
by

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## Abstract

A method is proposed to estimate the degree of tooth wear of a drill bit by comparing its actual drilling performance, measured in real time, with the theoretical performance of the same bit when calculated from the properties of the bit, a knowledge of the operating conditions and the strength of the rock being penetrated. To do this, it will be necessary to make measurements of the properties of the rock as, or shortly after, it has been penetrated. Instruments are currently available to make these measurements, but sufficient data to test the method were not available to the author at the time of writing this note. As an alternative, simulation techniques have been used to demonstrate the method in principle.

## Introduction

A driller always wishes to know the state of wear of his drill bit, but without having to remove it from the hole. Observing a decrease in the rate of penetration of the bit is, however, not sufficient evidence unless the strength of the rock being penetrated is also known. In general, a driller noting a decrease in the rate of penetration of the bit is unable to say whether it is because the bit teeth are worn, whether the bit is choked by an accumulation of sticky cuttings (bit balling) or whether the bit is still in good condition and is simply penetrating a more resistant formation.

There have been many efforts to distinguish between these conditions. Burgess and Lesso (1) proposed the approach of cross-plotting (torque/weight on bit x bit diameter) against the (dimensionless rate of penetration), thus, in effect plotting a "coefficient of friction" between bit and rock against the bit's aggressiveness. The ratio of the two parameters was found to change with the degree of wear, and so it could be interpreted as a measure of wear. The model was first developed for roller-cone bits, and was then extended to PDC bits (2). Unfortunately, it was found that the ratio also varied with rock type, so the measurement was unreliable unless the rock type was known. Another approach, by Cooper et al., (3) (applicable only to roller-cone bits) determined tooth height and hence tooth wear from changes in the vibration signature of the bit, but although the method was demonstrated in the laboratory, it proved impossible to transmit sufficient vibration data from the bit to the surface under field conditions to make the measurement.

In essence, since the bit rate of penetration depends on both the wear state of the bit and the rock strength, an estimate of the state of wear can only be deduced from the rate of penetration if the rock strength is also known. In a real drilling situation, it is impractical to recover samples of the rock being drilled for independent mechanical testing on surface, and the only downhole "mechanical testing device" is the bit itself, whose properties we are trying to separate from those of the rock. What is needed is an estimate of rock strength obtained independently of the bit. This could be used to calculate an expected rate of penetration of a new bit. Any difference between the expected and actual rates of penetration might then be attributed to bit wear.

## A Possible Approach

Methods are steadily being developed to determine rock strength from non-mechanical measurements. Many are based on an interpretation of the sonic log, augmented by information derived from a porosity log and/or the natural gamma ray emission. Such measurements are capable of yielding estimates of rock compressive strength, mineralogy and other properties that are of value in predicting drilling performance (4, 5). Further, they are increasingly becoming available in real time as the well is being drilled, from various Measurement-while-drilling (MWD) instruments.

A drill bit is a device for measuring rock strength to the extent that the bit rate of penetration depends on the strength of the rock. However, the connection between the two is not at all direct, since rate of penetration also depends on all the bit operating parameters and, critically, on the state of wear of the bit. The relationship between bit rate of penetration and rock strength has, however, been exhaustively studied in the form of various drilling models and these are thus available to relate rock strength to rate of penetration. (See, for example, refs.6, 7, and 8)

The proposal is therefore simply to take such a drilling model and feed into it a known set of operating parameters plus a rock strength derived from the logging measurements. This will yield a theoretical rate of penetration of the bit. If this rate of penetration is now compared with an actual rate of penetration, any difference can be interpreted to determine the state of wear of the bit. A real-time estimate could be made for a bit drilling in the field if the required log data were derived from an MWD unit mounted in the drill stem and the data were then combined with the current rig operating parameters. The field rate of penetration would be measured directly.

## Experiments

To test the idea, one needs a set of log data from a well to compare with the drilling record from the same well. For the application envisaged, both sets of information must be available in real time, but a test may be carried out off line. Data with the required degree of precision were, however, not available at the time of writing. Instead, the following procedure was adopted to see if the method could, in principle, provide the required information.

Data were obtained for a well for which foot-by-foot wireline logs were available, and for which some operational parameters were known. These included the average drilling parameters (weight on bit, rotary speed etc) and the state of wear of the bit at the end of the bit run. The log data were used to construct a lithological column that included information on rock strength and abrasivity. The lithological information was then passed to a drilling simulator (9) together with the set of known field operating conditions. The simulator was run and tuned until it reproduced the same total time for the bit run and the final state of wear of the bit recorded in the field. This procedure has been described elsewhere (10). These operations produced a "synthetic drilling record" that was believed to be close to what had been experienced under the actual field conditions. Most importantly, the record included the changing drilling response as the bit wore.

The next step could have been to calculate a theoretical rate of penetration for an unworn bit over the same interval, using the same lithological input information as had been used for the simulation. Such a procedure would, however, have generated a set of measurements with different depth increments from the synthetic drilling record, and this would have required a feasible but tedious set of interpolation steps before being able to match the two data sets. Instead, it was decided to invert the data from the synthetic drilling record to derive values for the apparent rock strength as a function of depth. This was done by an iterative process in which the kernel of the drilling mechanics algorithm in the simulator was used to estimate the rock strength required to give a particular rate of penetration. The iteration was stopped when the "field" rate of penetration was equaled.

The iteration was done without any knowledge of the state of wear of the bit, as would have been inevitable in the field. Thus, the estimate of the rock strength derived from the synthetic drilling record gradually rose above its true value as the bit run proceeded and as the bit became worn. This record is shown in Fig 1.

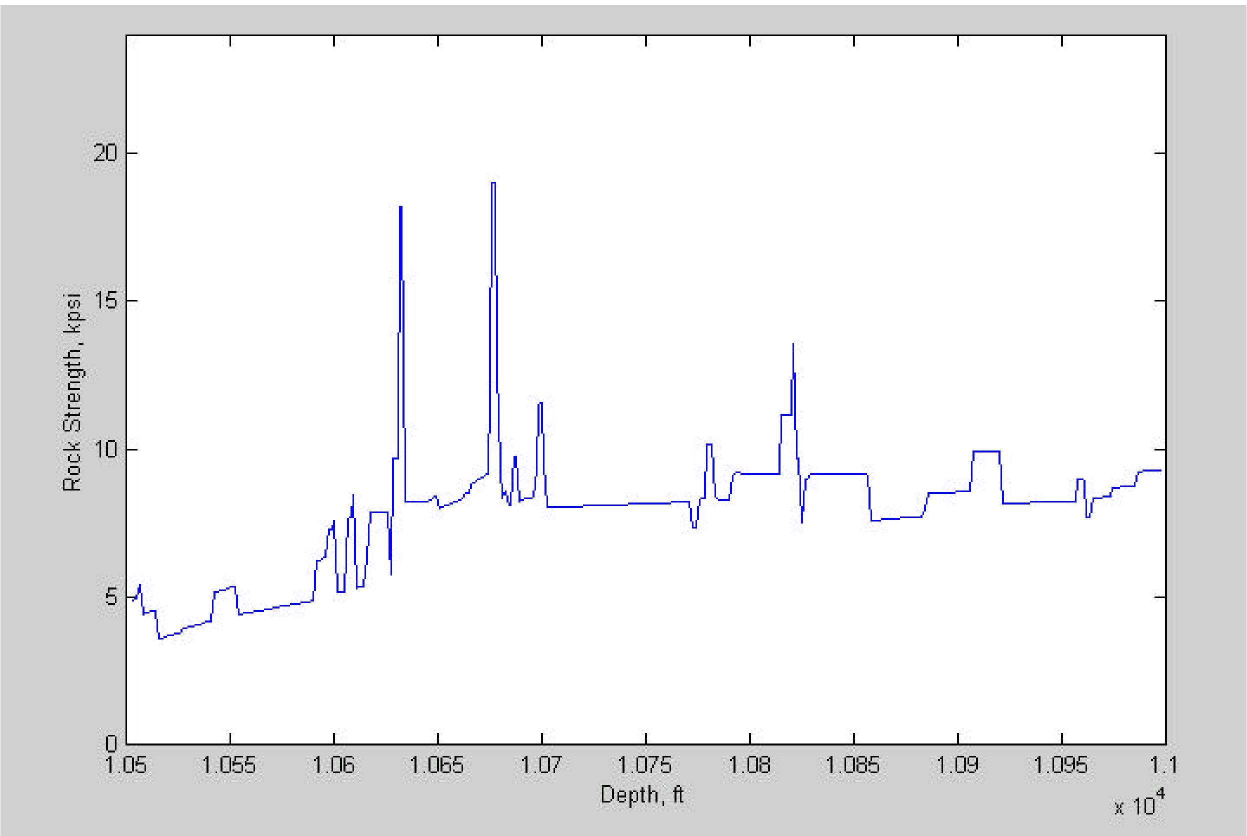


Fig 1. Rock strength estimated from the drilling record.

The record runs from 10,500 to 11,000 ft. The upper part of the interval, between 10,500 and 10,600 ft consists of sandstones. The interpretation shows them to have a compressive strength of 4,000 to 5,000 psi. Note, however, that the estimated strength increases over the interval. In reality this is because the bit is wearing, and so, since the rate of penetration is decreasing, the algorithm deduces (incorrectly) that the rock strength is increasing. From 10,600 ft to 10,700 ft, there are sands interspersed with limestone bands, some of which are very hard. The bit continues to wear over this interval, and so one can have less and less confidence in the absolute values of the rock strength that are being calculated. From 10,700 ft to the end of the bit run, the lithology consists mainly of shales with occasional carbonate stringers. Over this period, the estimate of rock strength is relatively constant, and so (supposing that the rock is not becoming steadily softer) one can infer that the bit wear is not increasing very much.

We now suppose that the driller has access to real-time MWD data from which he can obtain an independent estimate of the rock strength. When this is done and the log-derived rock strength is compared with the estimate derived from the drilling record, the plot shown in Fig. 2 is obtained.

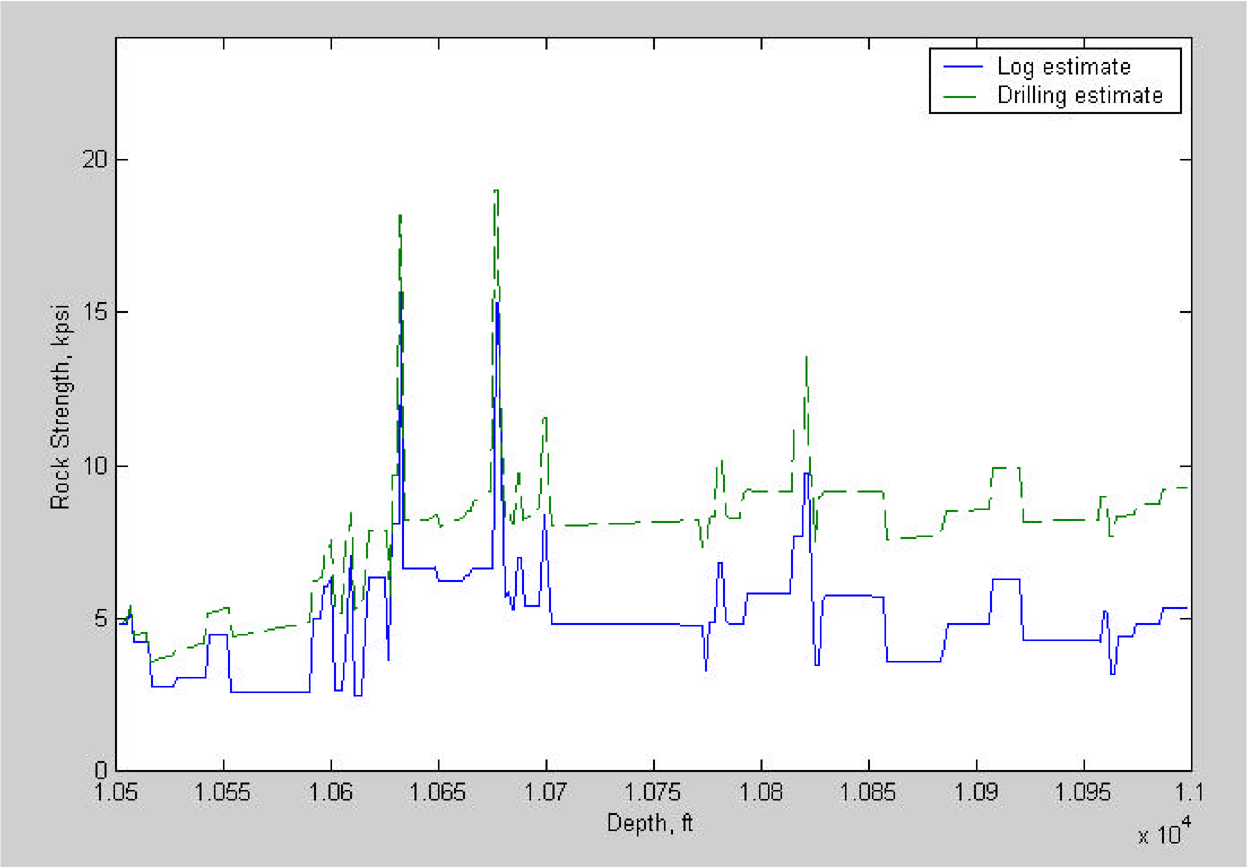


Fig. 2. Comparison of rock strength estimates obtained from drilling data and log data.

This clearly shows the steadily increasing distortion introduced into the estimate derived from the drilling data by bit wear. We see that substantial wear occurs in the sands in the upper portion of the interval, that more wear occurs in the section with the strong limestone stringers, and that relatively little additional wear occurs in penetrating the shales from 10,700 ft downward. We also note that, as a result of the bit wear, the shales were estimated from the drilling record to be about twice as strong as they really are.

It is now a relatively easy matter to take the drilling mechanics algorithm and to run it using the rock strength deduced from the log data. The state of wear of the bit is then adjusted by the algorithm until the rate of penetration observed in the field is matched. In a field application, this would be done in real time on the rig. The same process was carried out in the present case on a foot-by-foot basis to demonstrate the development of the bit wear. The result is shown in Fig 3.

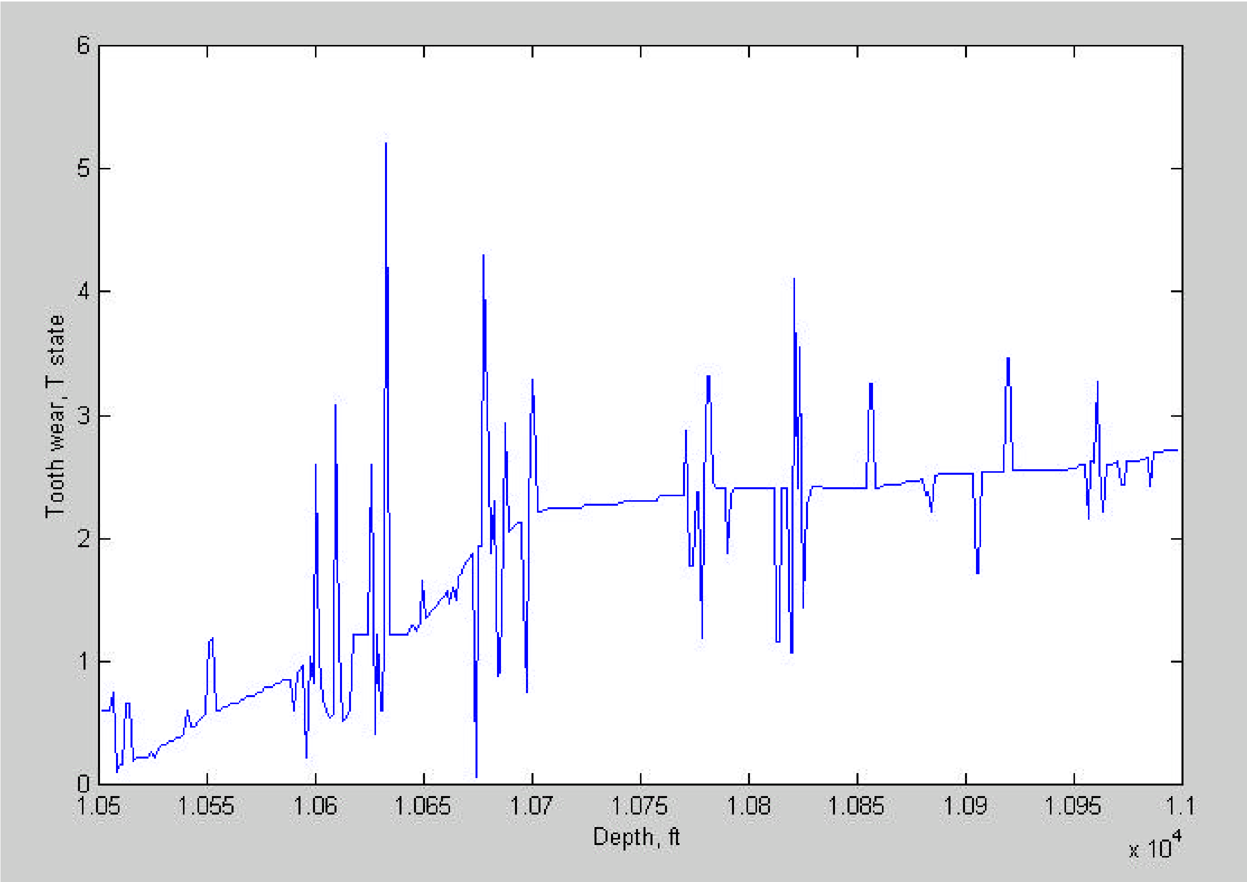


Fig. 3. Bit wear estimated by comparing log-derived and drilling-derived rock strengths.

The figure shows the tooth wear state presented as a "T" value (eighths of the original tooth height worn away) as a function of depth. As expected, it shows a progressive increase in wear. There is significant wear in the sands in the early part of the bit run, some severe wear after 10,650 ft in the sequence of sands and hard carbonates, and relatively little wear in the shales.

The sharp spikes that punctuate the curve are artifacts. They result from the fact that the drilling simulation data were calculated on a minute-by-minute basis, with the rate of penetration being estimated from the rock strength known for the depth at the beginning of that minute. If the rock type or strength changed over the distance that was calculated to have been penetrated during the minute, the change would not have been recognized until the beginning of the next minute (when the rock type and strength was checked again). Hence, if, for example, a harder layer had been entered during the minute in question, the simulation would have estimated a higher rate of penetration than in reality. This would have been interpreted by the wear algorithm as an apparent increase in bit sharpness, or reduced wear. The opposite effect would have occurred if the rock strength had decreased. For subsequent minutes, unless there was a further change in lithology, the algorithm would revert to the correct answer

## Discussion

It must be emphasized that although the lithology and log data that have been used for this demonstration were real, the drilling data were synthetic. Hence the results presented above cannot be accepted as having proven that it is possible to measure bit tooth wear in a real field situation. Rather, the objective has been to demonstrate an approach that should be feasible if such drilling data are available.

Much will depend on whether the algorithm used to infer the state of wear of the bit from the difference between the two estimates of rock strength is a good reflection of what is happening down hole. Making accurate estimates of bit rate of penetration from the rock strength (or vice-versa in the present case) is notoriously difficult in view of the large number of parameters that have to be matched. However, in the present case, a critical advantage is the fact that, at the beginning of each bit run, the driller is presented with a precise measure of the rate of penetration of his exact bit in new condition, in the well, the lithology and the set of operating conditions that are of interest for his present concern.

Thus, the requirement will not be to predict the rate of penetration of the bit from first principles, with the attendant requirement to supply a large number of parameters relating to bit geometry, the rock, the down-hole pressure environment etc.etc., but to make a simple normalization of the simulator calculation so that it matches the known rate of penetration of the bit at the beginning of the run. Then, as long as the drilling environment does not change by a very large amount, and as long as the drilling algorithm is not seriously in error, the prediction should be reasonably accurate. Note that the change in bit rate of penetration as a function of wear is generally large (by a factor of three or more times for a TCI bit, and for more than ten times for a typical PDC bit). Changes of this magnitude should overshadow any errors in estimating, for example, the change in rate of penetration as a result of changes made in weight on bit or rotary speed, or resulting from mis-calculating the rock strength from the log data.

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