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A New Method for Data Correction in Drill Resistance Tests for the Effect of Drill Bit Wear

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Abstract

The determination of the drilling resistance of abrasive materials is strongly affected by the continuous and progressive wear suffered by the drill bit tip. In order to have reliable and comparable results, the actual drilling resistance has to be corrected for the drill tip abrasion. The paper presents a new methodology to carry out these corrections. This method avoids the obtention of negative results and is able to deal with regular and irregular wear behaviour, such as when the wear rate increases with the drilled length.

Keywords: DRMS, drilling resistance, drill tip wear, wear correction, stone resistance, abrasive stones

Eine neue Methode zur Korrektur der Ergebnisse von Bohrwiderstandsmessungen, um den Einfluss des Abriebs am Bohrer zu berücksichtigen

Zusammenfassung

Die Bestimmung des Bohrwiderstandes abrasiver Werkstoffe hängt stark von dem dauernden progressiven Abrieb, den die Spitze des Bohrers erleidet, ab. Um zuverlässige und vergleichbare Ergebnisse zu erhalten, ist es notwendig, den gemessenen Bohrwiderstand hinsichtlich des Abriebes der Bohrerspitze zu korrigieren. In diesem Beitrag wird eine neue Methode vorgestellt, mit Hilfe derer die entsprechenden Korrekturen durchgeführt werden können. Mit dieser Methode erhält man keine negativen Werte mehr. Außerdem können sowohl gewöhnliches als auch ungewöhnliches Abriebverhalten, bei dem beispielsweise die Abriebgeschwindigkeit mit fortschreitender Bohrlochtiefe ansteigt, bei der Korrektur berücksichtigt werden.

Stichwörter: *Bohrwiderstandsmesssystem (BWMS), Bohrwiderstand, Abrieb Bohrerspitze, Abriebkorrektur, Steinfestigkeit, abrasive Natursteine.*

1 Introduction

The characterization of strength parameters is an important parameter in the study of stone and related materials. When large specimens are available, compressive, bending and tensile strength can be easily measured and several other strength related parameters can also be determined. However, among this large number of testing methods, only a few can be used on site and applied directly on stone surfaces. Finally, the output of most of these methods is a value characterising either the bulk of the stone (such as the compressive and bending strength) or its mere surface (e.g. surface hardness). But none of these methods are capable of measuring in an easy way the variation of strength with depth, a relevant information that can serve to indicate a decay process or to determine to what depth a consolidation has been achieved.

The development of the microdrilling tools for the characterisation of stone [1] was viewed as an encouraging procedure and other researchers have tried to improve the methodology. The DRMS (*Drilling Resistance Measurement System*) [2, 3] represented an extraordinary improvement in the hardware and the technological concept and definitely placed this testing method among the most important ones both for the laboratory and for on site testing of stone and related materials. The initial results were very encouraging and they represented a step forward in some critical areas in the preparatory work for conservation interventions. The characterisation of decay profiles, the identification of past consolidation treatments and the study of the performance of new stone consolidants are some of the already demonstrated uses of the instrument [4].

The test results are extremely dependent on the technical characteristics of the instrument and the material tested so that all the details that may influence the final results have to be duly taken into account. Since the test results are obtained through a process of progressive cutting of the stone both the stone properties and the drill tip constitution and its three-dimensional geometry are relevant. Some of the parameters that influence the final results can be discarded when the problem can be solved by comparison. For instance, two drill tips made of tungsten or diamond will give different absolute drilling resistances, but both can be perfectly usable when comparing consolidating treatments. The same reasoning applies to the drill bit tip geometry.

It is well known that materials, such as stones, have distinct abrasiveness towards cutting tools, and the presence of quartz is a distinctive factor in this respect. Wearing of drill tips is a continuous process that reduces the effectiveness of the cutting process and results in a progressive increase in the drill resistance offered by the stone to the drilling process. Obviously, this increase in the drill resistance is only apparent and has to be corrected in order to achieve comparable results. The present paper proposes a new methodology for correcting drilling data by taking into account the wear of the drill tip in DRMS instruments. The reported drilling values for Sander sandstone were taken with a diamond drill bit with 5mm diameter and a flat tip, operating at 600 rpm and at 10 mm/min advancing rate.

2 Background

Since the first characterisation studies carried out with drilling instruments in abrasive stones, authors have realised that some corrections were needed in order to have comparable results. To our knowledge, the formula that Pfefferkorn [5] proposed was the first feasible methodology for correcting drilling data in abrasive stones. This formula was first defined for a different kind of drilling system, the German DURABO testing equipment and was later reformulated by Singer et al.[6] to cover also the DRMS testing data. In a subsequent section of the paper, a comparison between the two correction methods is presented.

In current situations, under extreme heterogeneity conditions, the wear of drill tips is a continuous and progressive process that occurs at rates that may vary from zero [7] to pretty large values. A common situation of a moderate abrasive stone is illustrated in Fig. 1.

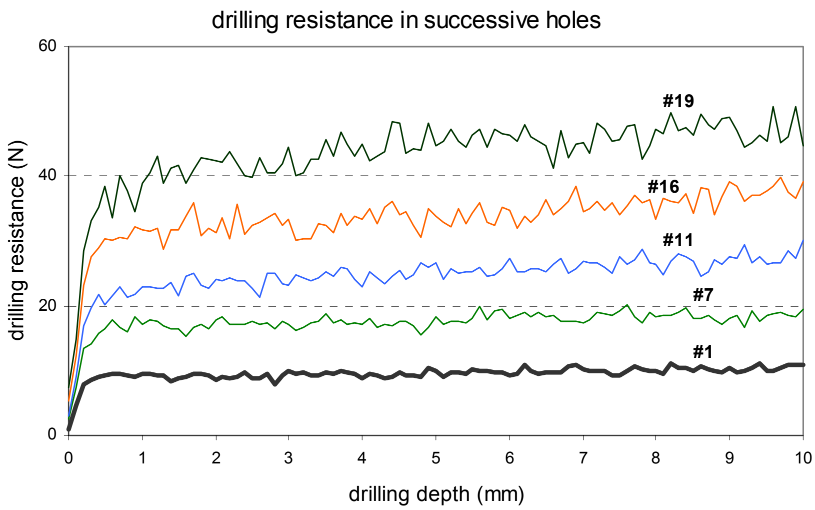

Figure 1: Drilling resistance graphs for Sander sandstone after 1, 7, 11, 16 and 19 holes made with a unique drill bit

Considering that wear is a regular and continuous process, the correction will necessarily be dependent on the drilled lengths up to the particular correction point. As a first consequence, it is clear that a proper individual register with the past drilling history has to be established for each drill bit. Since different rocks have different abrasive potential, it should also be stressed that mixing up drill bits and stone specimens may lead to unsolvable confusion. Therefore, as a good code of practice, we would recommend that each drill bit be used in well defined conditions, as far as possible avoiding any mixed uses of drill bits during any characterisation procedure.

Taking into account the regular increase of resistance with the drilling length, authors were attracted to correct the actual resistance at a given point by subtracting a value computed by multiplying the drilled length with the increased resistance rate. Depending on the specific case under study, the abrasive rate can be computed with values taken from the successive graphs or determined with specific drill holes made in a similar stone specimen—taken as a reference—with holes performed at regular intervals during the drill bit operating life. In our experience, any correction due to drill bit wear has to be made with correction data obtained in the same stone material. That is to say, the correction factors cannot be extrapolated from one type of stone to another or based on an hypothetical "*Universal Reference Material*", since both ways will lead to erroneous results.

Fig. 2 represents the drilling resistances determined in a Sander sandstone specimen with a single drill bit along a series of 20 holes with a constant depth of 1-cm. The results represented in the graph are the "Mean resistance" between 2-8 mm (and the standard deviation) versus the "Total drilled length" up to the successive hole. For plotting the data, each value was "attributed" to the middle of this interval (i.e. 5-mm). The plotting took into account the total length drilled until the point of each new average value (i.e. 5, 15, 25, 35 mm, etc.). At regular intervals (every 5 holes), two consecutive holes were made in an artificial material (ARS) in order to evaluate the feasibility of using it as a reference material for any stone to be tested. The results are striking and unexpected. Although both materials start at similar drill resistances the wear effect is felt in Sander stone with a substantially higher rate increase. Whatever the reason that we might put forward for this effect, it is absolutely clear that the wear rate measured in ARS is not appropriate for correcting the Sander sandstone values.

The inclusion of data taken in ARS also illustrates the inconvenience of mixing two materials with different abrasiveness. Since ARS is virtually nonabrasive, the inclusion of that data in the sequence of holes made in Sander promotes a shift in the regression lines. If such a situation happens and a correction procedure is to be carried out, the length drilled in ARS should not be included when computing the total length drilled with the drill bit in question.

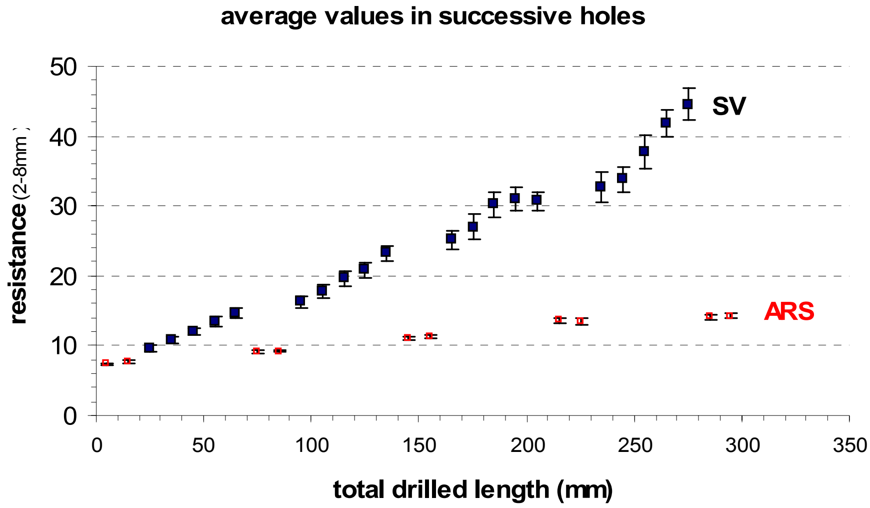

Figure 2: Evolution of mean resistance values on Sander specimens and on ARS due to drill bit wear. The drilled lengths on both materials are added in this representation

Minor changes in the characteristics of the cutting tip (hardness, geometry, construction defects, etc.) will influence its performance, that is why it is not advisable to extrapolate the correction factor from one to another drill bit, even when drilling in similarly abrasive stones. For supposedly similar tools working in the same stone material, the differences may be of minor amplitude, but in the absence of well demonstrated cases, the extrapolation is to be avoided as far as possible. Since any change in the operational parameters (drilling rotation speed and penetration rate) will influence the results, it is essential that the same conditions be used during the entire process. Any change in these parameters would require the conversion of values to the reference conditions, but this extra operation would introduce additional variations and would result in a loss of accuracy.

In order to be on the safe side of the problem, the best solution is to “produce” the correction function “*au fur et à mesure*” that the drilling tests are made, for which a testing sequence is proposed herewith. Based on what has been said, it should be emphasised that the methodology here proposed is designed to be applied to any single drill bit, from its starting hole until it is no longer suitable as a testing device.

3 Proposal of a New Testing Methodology

For values averaged over a certain drilling length and for very homogeneous materials the above mentioned correction method cited from literature gives acceptable results. However, when very low values are found at a certain depth in the graphs, the subtracting of a certain value computed on the basis of the "average stone" may lead to negative resistance values that result physically meaningless, a fact that highlights the need for improving the applied correction concept. The introduction of such a new concept is the aim of the present methodology.

The basic idea of this new concept assumes that the corrected values are a fraction of the measured ones and that this correction fraction can be determined experimentally during each characterisation operation. The following procedure has been applied to a certain number of cases studies and is given as an example of a feasible and appropriate methodology.

Assuming the terminology:

> **Stone A** – is the stone under study (it can be extended to any material other than stones provided the DRMS instrument is applicable),
>
> **Correction specimen** – is a piece of the same material ("stone A") left undisturbed where the correction factor is to be determined,
>
> **Correction holes** – are the holes made in the "correction specimen",
>
> **F_0** – is the drilling resistance obtained in the first hole made in the "correction specimen" and it represents the best approximation of the "true" Drilling Resistance of the material. As seen later, this value is also susceptible to be corrected,
>
> **Average resistance** – is a value computed between any two defined points along the drilling resistance graph. It can be obtained directly in the instrument or in the exported Excel files.

The following methodology is proposed:

- I Select a specimen of "stone A" on which the correction holes are to be made. This will remain as the "correction specimen",
- II Make the first hole with the new drill bit in the "correction specimen" (1cm depth). The average resistance of this hole shall be called F_0. In order to avoid the influence of the first 1-2 mm, where the drill bit tip form has a large influence, the interval between 2 and 8 mm is suggested,
- III Drill the required test holes in the specimens under testing,
- IV At regular intervals of the drilling life of the drill bit, drill a new 1cm hole in the "correction specimen" (these resistances are called F_i),

V The interval between two correction holes has to be adapted according to the abrasivity of the stone. It shall be shorter for more abrasive stones and longer for the less abrasive ones,

VI For the case of Sander sandstone, for a diamond drill bit, the correction holes may be carried out at every 50 mm of drilling length until five reference holes are available. From then onwards, one new reference hole should be made at every 100 mm.

The correction function (assuming a linear regression) can be computed with a minimum of two holes, but accuracy will increase when a higher number of holes is available. Since the process of drilling will affect both the correction process and the real testing data, it is inappropriate to drill a larger number of holes beforehand, since the extrapolation for subsequent drill holes will not necessarily apply. Therefore, it has to be considered that the correction of the very first holes may not be "perfect" and will certainly require a subsequent revisiting for finding more accurate results.

When feasible, it is advisable to wait for a certain number of correction holes, in order to have a reliable correction function, and then proceed to apply it to the existing drilling data. In general, this limitation is expected not to be very critical and, in our experience, this procedure has always been compatible with the normal testing routine. Most of the times, when a report with the analyses is to be produced, enough correction holes are already available to determine a correction factor.

4 Correction Procedure

The implementation of the proposed correction methodology can be made through the following protocol:

I The drilling resistance obtained at every correction hole shall be averaged between 2 and 8 mm,

II Successive F_i resistances shall be divided by F_0,

III The average resistance of the hole is assigned to the starting point of that specific hole, that is to say, for the first point, F_1/F_0 shall be plotted at x=0mm; for the hole drilled between 80 and 90 mm, the result F_i/F_0 shall be plotted at x=80 mm,

IV For all the available correction holes, plot the drilling resistance in function of the total length drilled until that specific hole,

V In ordinates plot F_i/F_0. In abscissa plot the total drilled length until point i, VI Adjust a regression line to the correction data. Use one or more straight lines according to the type of data. See Fig. 3 for easier understanding,

VII The first regression line shall, in principle, cross at point XY (0;1) or very close to it. Large divergences from this assumption shall be analysed carefully and explained before proceeding with the correction procedure,

VIII Determine the regression equation for each regression line.

Once the regression equations are available, the drilling data can be corrected automatically, point to point, directly in the Excel files converted from the *.*txt* files exported by the software resident in the DRMS equipment.

The general correction formula is:

$$Fc_i = \frac{Fm_i}{a + bx_i} \tag{1}$$

where:

Fc_i = corrected resistance at point *i*

Fm_i = measured resistance at point *i*

x_i = total length drilled with the concerned drill bit until point *i*

a = ordinate at the origin. For the first part of the graph, it should be very close to one

b = angular coefficient of the regression line,

The full procedure is illustrated herewith by means of a theoretical example. Fig. 3 displays two theoretical graphs with evolution of the drilling resistance in function of the drilled length. One has a single linear trend (A) and another has two distinct trends (B). Once the correction lines are defined, it is possible to correct the actual drilling resistances at any depth, by means of an appropriate Excel sheet where the DRMS data is listed.

For correcting of data in Fig. 3 (line A), these fictitious data have as regression equation:

$$y = 1 + 0.1x$$

and the correction at any given point *i* , occurring at a drilled length x_i, will be made as follows:

$$Fci = \frac{Fmi}{1 + 0.1x_i} \tag{2}$$

For the graph B, a regression equation fits until 25 cm and a second one from there after. The two displayed regression lines illustrate this assumption.

Assuming just for simplicity that the two regression equations are:

$y = 1 + 0.25x$, valid until 25cm, and, $y = 5.8 + 0.04x$ valid after 25cm.

The correction formulas would result in:

$$Fci = \frac{Fmi}{1 + 0.25xi} \tag{3}$$

applicable until 25cm, and:

$$Fci = \frac{Fmi}{5.8 + 0.04xi} \tag{4}$$

applicable after 25cm.

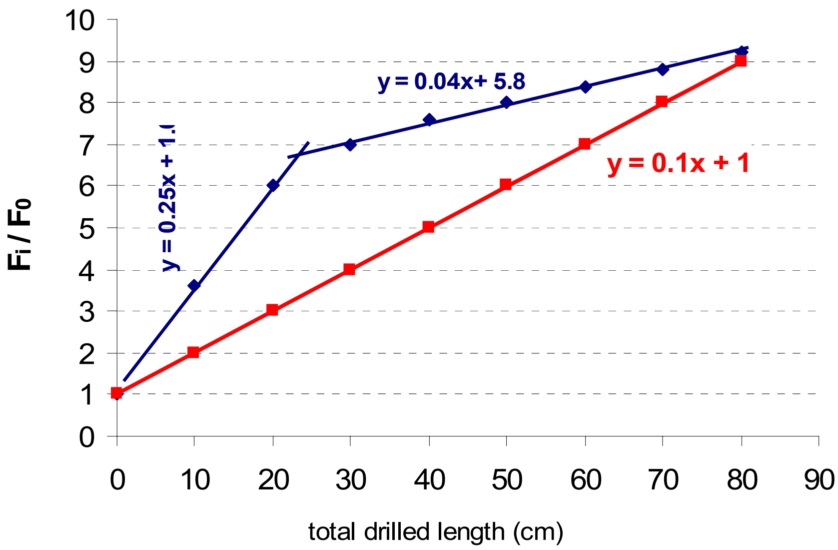

Figure 3: Examples of two hypothetical correction functions for two different materials

For a completely non linear trend, either a single non-linear regression function can be fitted into the data and then it is simple to use that function to correct the data, or such a regression function cannot be found and corrections have to be made by estimating a correction factor valid for any given interval successively until the end of the curve or until a linear trend can be fitted in.

As these formulas show, the correction is made with a fraction, and therefore **no negative values will ever be obtained**. This will solve the problem raised with graphs that show very low values and that need a substantial correction due to tip wear. Furthermore, this seems to be the logical way for correcting experimental data when peaks and lows are found one close to the other. Naturally, higher peaks will get a larger correction and lows a lower correction, which seems to fit reality, at least as far as we understand it so far.

5 Application to Sander Data

In the course of the MCDUR project, several holes on two specimens of Sander sandstone (SV27 and SC 89) were made by BSCO (Bayerisches Landesamt für Denkmalpflege). In these tests, two drill bits were used, DM 32 and DM 31, respectively. From time to time (around every 5 holes), two holes on ARS (an artificial ceramic material) specimen were carried out. The data used for determining the correction function are displayed in Fig. 2. For the reasons explained above, the length drilled in the ARS was disregarded in this correction procedure.

The plot with values from the correction drill holes for Sander SV is presented in Fig. 4. In the graph, four distinct regression lines were fitted in the data. As stated in section 3, the mean values are assigned to the initial point of the respective hole and F_0 (the first hole made, used as reference) is plotted at “0 total drilled length”. “IP” are the inflection points that indicate the depth from thereafter the application of the new correction shall be adopted. In the present case, the first regression data shall be applied from 0 until 70 mm, the second set of data from 70 until 130 mm, the third set from 130 mm until 160 mm and the last from 160 mm onwards.

In many real cases, we expect that one single correction line be enough to correct the actual data. However, since the equipment provides data that are directly exported to a computer, the mathematical correction for two or more lines is simple and straightforward and thus there is no justification to oversimplify the process with the consequent loss in accuracy.

Adopting the correction procedure outlined in the section above, the original curves of Fig. 5 are transformed into the corrected ones shown in Fig. 6. The complete set of 19 holes fit in a very narrow band fact that demonstrates the appropriateness of the correction procedure. Taking into account that the raw data include peaks due to the occurrence of harder minerals, such as quartz grains, together with softer zones,

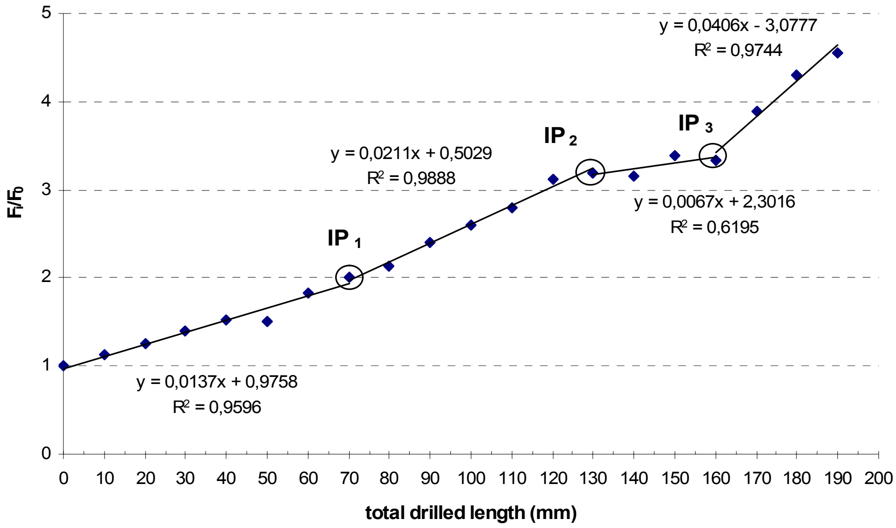

Figure 4: Correction functions in SV Sander sandstone. IP indicate the points where a new wear rate starts and a new set of correction parameters should be used

the distribution of the all 19 plots in such a narrow band can be considered as a "perfect" correction.

When all the plots are presented in a bunch, the effectiveness of the correction procedure seems correct enough, but this result can also be seen when analysing the plots individually. Fig. 7 shows a few plots where some aspects can be analysed in some more detail. The first plot, Fig. 7a), shows the original graph of the first drill hole (from which F_0 was computed) together with another one corrected with the general function used for the subsequent plots. As can be seen, the correction is perfectly noticeable and therefore it allows a more accurate value for F_0 to be determined. In special cases, when very high accuracy is required, this correction is recommended and consequently, the correction procedure can go through a second iteration starting with the correction of F_i/F_0 ratio and proceeding as before with the next correction steps. In fact, wear of the drill bit starts from the very first drilling rotations and the corresponding resistance increase can be measurable since then and therefore, this further correction step may be perfectly justified. Fig. 7b), c) and d) show raw and corrected drilling data from three individual holes compared to the corrected F_0 plot. These graphs are in very good agreement of the individual corrected plots with F_0 plot, thus demonstrating the accuracy of the correction methodology.

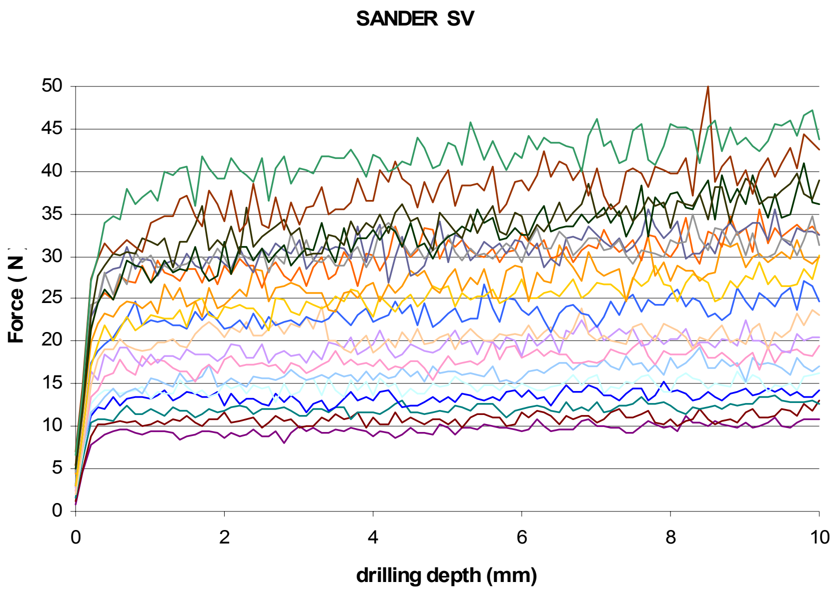

Figure 5: Original plots of 19 holes in Sander sandstone (SV) before correction

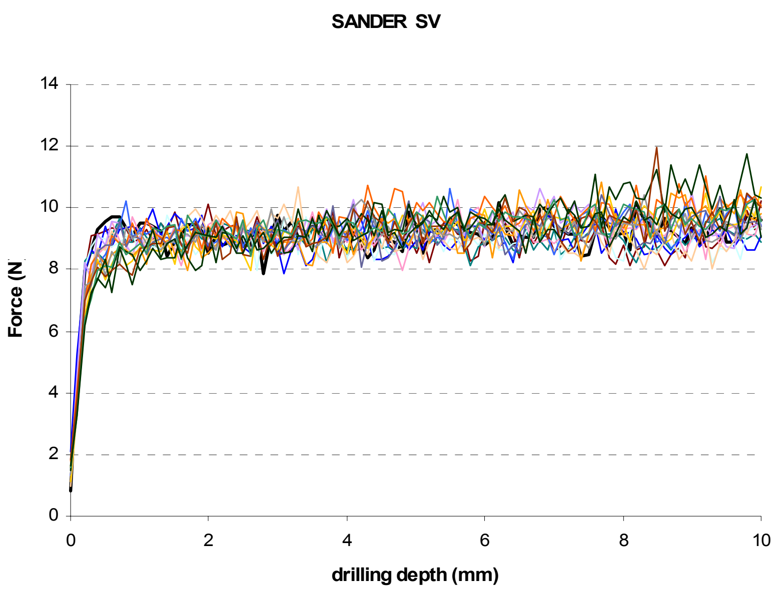

Figure 6: Data from Fig. 5 after correction

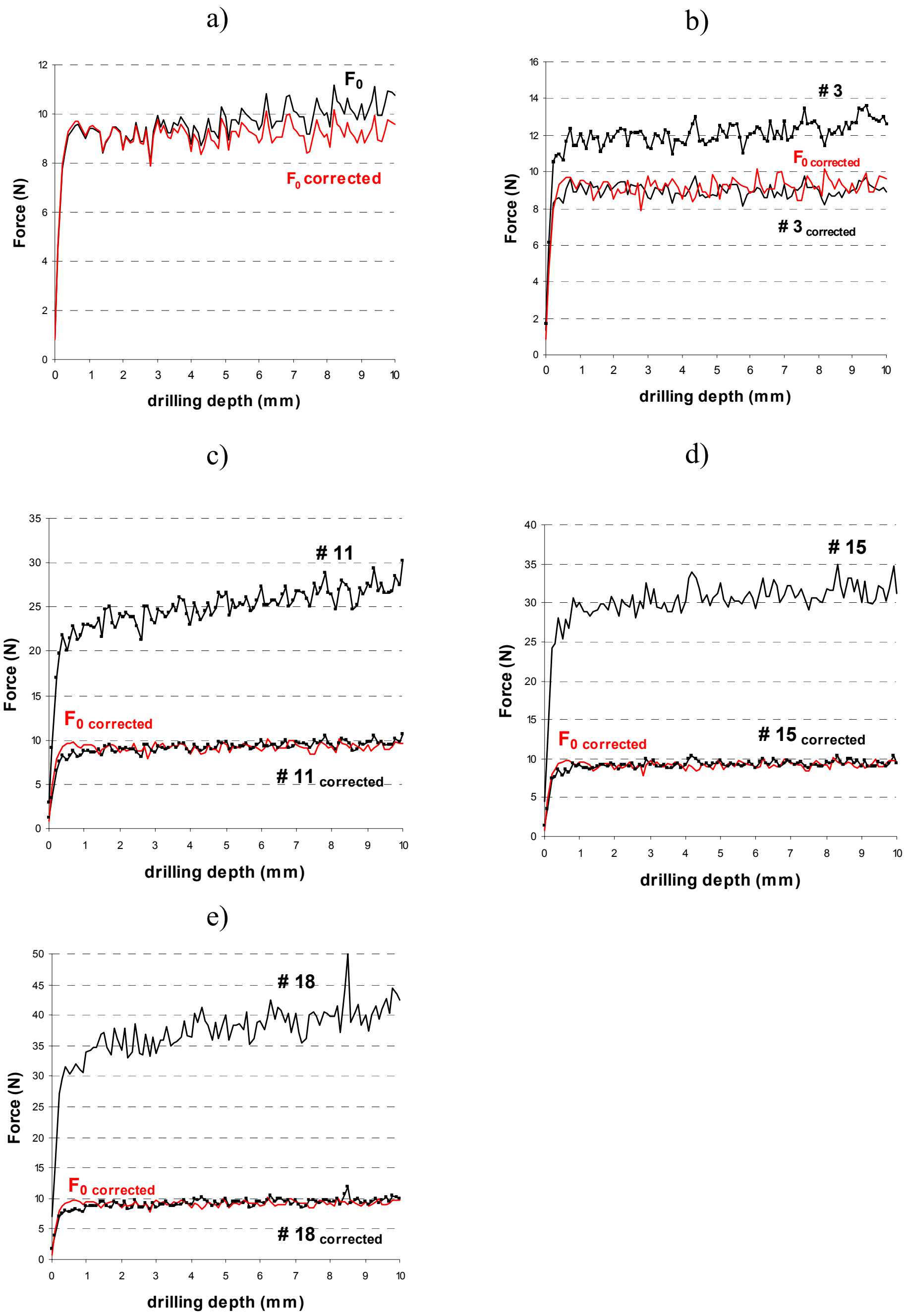

Figure 7: Examples of SV plots. a) F_0 plot before and after correction; b), c) and d), respectively, holes # 3, #11, # 15 and #18 before and after correction, compared to the corrected F_0 plot. The plots to be corrected were taken one from each of the four different wear rates.

One of the leading motivations of this study was the fact that previous correction proposals lead to negative resistance values, whenever very low values occur interspersed in the drilling data. These values may occur when a very weak layer is crossed or when degradation has produced a fracture or a very weak zone inside the stone. In order to test the result of the proposed methodology when applied to such situations, a few fictitious graphs were generated having very weak zones introduced. For this purpose, original Sander drilling graphs were transformed by means of a sequence of points manually modified in order to simulate very weak zones. Then, we proceeded with the correction function used for those specific holes according to their position in the drilling sequence.

Fig. 8 shows two pairs of curves taken from two distinct phases of the drill bit wear stage. All the plots are real except the troughs of the "low" values that were manually introduced. In each figure, the upper plot represents the registered data and the lowest one represents the corresponding corrected values. Although departing from values close to zero in the artificially made troughs, the corrected plots show no negative value, as expected from the mathematical formula used in this methodology.

Fig 9 shows these same results but now compared to the values corrected with one formula that uses a subtraction instead of a fraction. As can be clearly seen, the previous correction formula leads to negative values while with the formula proposed in the present paper no negative values are obtained.

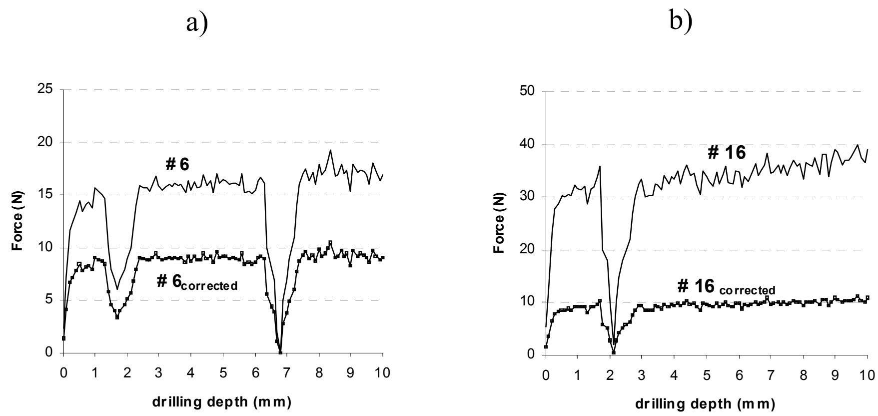

Figure 8: Correction of drill plots where simulated zones with very low drilling resistance were introduced in actual SV curves. Plots for holes # 6 (left) and # 16 (right) before and after correction

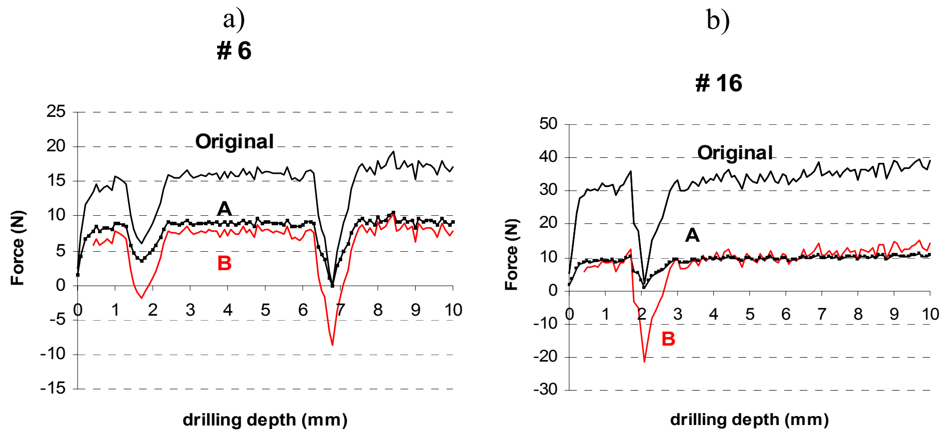

Figure 9: Correction of drill plots of Fig. 8 using the proposed methodology (A) compared with one subtracting formula (B). Notice the negative values obtained with the subtracting formula (B) and its absence when the new one (A) is used

6 Discussion and Conclusions

The proposed methodology is suitable to correct drilling data affected by progressive wear of the drill bit tip in abrasive stones. The methodology is simple to use but it requires a systematic method in order to have reliable data in all the time span of the drill bit service life. As far as the present knowledge permits, the correction function has to be determined in the same material, since wear is not equal in materials with different compositions. The simplest method is to select a similar stone where correction holes are made periodically in order to have the wear function well defined. If such a situation is not feasible, other possible alternatives have to be sought. In most situations, even when the drill tests are to be made in complex situations with severe decayed zones, the drill graphs most often show some zones where the "intact" stone can be characterised reasonably. Taking Figs 8 and 9 as an example of a series of drillings to be corrected and where no "correction specimen" was available, it would be acceptable to select the interval between 3 and 5 mm in the consecutive holes in order to determine the wear function. Once this function is found, all the process shall follow the proposed methodology.

As demonstrated above, the new correction methodology avoids the occurrence of negative values and corrects the resistance values in a proportional way. From a physical point of view it is not acceptable to have negative resistance values and the corrected graphs also suggest that a proportional correction formula is better than a simple subtraction. The possibility of adapting the correction formula during the drill bit service life makes the methodology very versatile and reliable. So far, the real cases in which this correction methodology was applied gave total satisfaction.

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7. In very soft and "non-abrasive" stones, we have found cases where the drilling resistance decreases, thus showing an improvement of the drilling performance. The best explanation for this "abnormal" behaviour was attributed to the polishing of the helicoidal grooves of the drill bit caused by the passage of the drilling cuttings leading to the improvement of their escaping paths.

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