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Log-derived Rock Strength Evaluation

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ABSTRACT

Several oil industry operations, like borehole stability, pore collapse analysis and hydraulic fracturing, demand rock mechanical knowledge that sometimes is unavailable or is only poorly known. Statistical relationships defined through dynamic and static rock properties, simultaneously determined in lab tests, yield a novel approach to continuously evaluate rock strength over whole depth well intervals.

INTRODUCTION

Rock strength determinations are commonly done through destructive lab tests in rock samples cored from specific depths of the target well. This procedure yields mechanical information only for the tested intervals and cost restrictions, in general, impede a huge sampling of the whole well. Sampling problems arises in importance especially in the case of thin-layered intervals.

The need for a continuous rock mechanical analysis, but avoiding a huge and time costly lab test battery, led to an indirect solution which uses the rock physical properties acquired by well logging geophysical runs. Velocity and density logs are the main ones that contain information about rock mechanical properties, Ohkubo & Terasaki (1977). Then the problem is reduced to find the relationships between the static mechanical properties of rocks, as measured in load frame tests, and the dynamic rock properties, as measured by ultrasonic well logging tools.

Two important factors must be observed for comparison between lab measured and log derived rock properties. First, environmental conditioning like pressure, temperature and saturation, should be the same in the lab as well in subsurface; second, possible occurrence of depth shifts between cores and logs should be corrected. To avoid the former problem, simultaneous tests have been done in the lab which measured static and dynamic rock properties in the same sample and, obviously, under the same general conditions, as shown in Montmayeur & Graves (1985). All core depths have been corrected to log depths to avoid the last problem.

A multiple regression model was defined based on the data acquired in the lab for a set of limestone and sandstone samples. This statistical model was applied in two depth intervals, one for each lithology type, and the predicted logs were compared with the sample strengths effectively lab measured, presenting encouraging results.

METHODOLOGY

The methodology for continuous rock strength evaluation was developed through five steps:

1- simultaneous tests with P and S waves propagation in rock samples during destructive tests in load frame;
2- statistical definition of the relationship between rock strength and dynamic parameters;
3- estimation of the in situ effective pressures;
4- if the S wave log is unavailable, estimation of it through the lab Vp/Vs ratio or using some petrophysical models from literature;
5- calculation of the strength log.

Steps 1 and 2 would be omitted for posterior rock strength log calculations.

SIMULTANEOUS TESTS

These are rock mechanics triaxial tests where are established the relationships between the imposed stresses and the resultant rock sample strains and, furthermore, P and S waves are propagated through the rock sample along the test. Thus, static and dynamic elastic constants as well rock strengths are obtained.

Triaxial tests are done with application of a initial hydrostatic confining pressure to cylindrical rock specimens (dimensions 100x50mm) followed by application of axial deviatoric stress. The deviatoric stress control system obeys to a constant and pre-defined axial strain rate, in such a way that if this rate is high, the deviatoric stress increases slowly, and if the rate is low, the deviatoric stress arises rapidly. On the other hand, the confining pressure level is defined according to the test target. If we are interested in measure the in situ rock properties it is left constant and equal to the reservoir effective pressure. It may be constant but in a different level for each rock sample, if the purpose is to obtain de Mohr´s circle. Finally, the confining pressure may be variable if the objective is to evaluate the possibility for occurrence of pore collapse in high porosity rocks, this last case also named axial strain test.

Eleven limestone samples, cored in wells from five distinct oil fields, were simultaneously tested yielding rock strength for confining pressure range from 5 to 50 MPa and dynamic shear modulus from 5 to 21 GPa. A set of 35 sandstone samples, cored in wells from five sedimentary basins, was also simultaneously tested. Confining pressure ranges from 0 (uniaxial test) to 50 MPa and dynamic shear modulus from 2 to 30 GPa. These data were used to obtain the regression function for each lithology type.

The elastic constants of simultaneous tests were calculated at half of maximum deviatoric stress, according standardization rules to define the linear interval of the stress-strain curve, ISRM (1983). Rock strength, in lab tests, is the addition of confining and maximum deviatoric stresses.

STATISTICAL RELATIONSHIPS

An exhaustive regression work was done to identify the better set of input variables able to predict rock strength (STRE) from environmental conditions (e.g. confining pressure, temperature and saturation) and well logging rock properties. Confining pressure (CONF) and dynamic shear modulus (GDYN) appeared as the most prominent set of input variables, in accordance with Dillon et al (1996). Using the data acquired in the simultaneous tests, equation (1) was defined and the coefficients **a**, **b**, **d** and **e** are separately defined for each lithology. STRE and CONF are in MPa and GDYN is in GPa.

$$STRE = \frac{\left(-b + \sqrt{b^2 + 4aCONF}\right)}{2a} + dGDYN + eGDYN^2 \quad (1)$$

where
a = 0.000892 **b** = 0.588805
d = 0.855462 **e** = 0.309565
for limestones, with regression coefficient R = 0.98, and
a = 0.001196 **b** = 0.195158
d = 0.886125 **e** = 0.133662
for sandstones, with regression coefficient R = 0.96.

Figure 1 and 2 are 3D plots of equation (1) for imestone and sandstone cases. In these figures equation (1) is represented by the surfaces, lab measurements are presented as open circles while the prediction error (difference between regression predicted and lab measured values) for each lab measurement is given by the associated solid bar. Figures 1 and 2 suggest, in general, a stronger linear relationship between rock strength and confining pressure for limestones in comparison with sandstones.

RESERVOIR EFFECTIVE PRESSURE

For a practical use of the regression equation (1) for a continuous rock strength evaluation it is necessary initially to define the confining pressure for each depth interval. This work assumed that the in situ confining pressure would be controlled by the overburden vertical stress, i.e., lithostatical stress minus the fluid column pressure, considering here that the porous space is interconnected over the whole stratigraphic column. Taking average densities for stratigraphic and pore fluid overlay columns, a constant gradient of 1.74 psi/m is assumed for confining effective pressure

$$CONF = 1.74 \times SED / 145 \quad (2)$$

where SED is the thickness of sediments (m), given by the depth minus the water depth, and the constant 145 is the conversion factor between psi to MPa, according to equation (1) units.

SHEAR WAVE VELOCITY PREDICTION

It is very common the S wave log do not be available, especially in older wells. In such a case laboratory compressional and shear waves velocities are very helpful to generate predicting relationships for S wave velocity from P wave velocity, as shown in Bastos et al (1998). Furthermore the possibility to check such prediction with lab measured S wave velocities arises its confidence level. Figure 3 is a crossplot of Vp and Vs logs acquired in limestone intervals of two wells. For these data a common linear regression was defined as

$$Vs = 0.4939\, Vp + 219.64 \quad (3)$$

where velocity units are m/s. In next section, equation (3) was used to predict Vs log for a limestone interval.

S wave velocity prediction can also be done through several models from literature: Greenberg & Castagna (1992), Krief et al (1990), Lira et al (1997).

STRENGTH LOGS VIA REGRESSION

In this section, two logs of rock strength are presented as real application examples, where one is for a limestone interval and the other is for a sandstone interval. Both strength logs were calculated using equation (1) and these wells were selected as consequence of the availability of lab tests for a comparative analysis between predicted strength logs and effectively lab measured rock strengths. Some core sample strengths were acquired in triaxial tests with constant axial strain rate, here simply named triaxial test, while others were tested without radial strain, here named axial strain test.

While the former test type is done under a constant confining pressure, the latter is done under an increasing confining pressure, thus avoiding any radial expansion of the rock sample with the deviatoric stress application. Equation (1) seems to have the same predictive capacity for both test types.

This work was done using available data obtained for drilling and production purposes and much of them were tested in confining pressure levels unequal to in situ confining pressures. Thus, strength corrections were necessary to take test confining level strengths to in situ confining level strengths, allowing the comparison between lab measured strengths and log predicted strengths which use in situ confining pressures defined by equation (2). This confining level strength correction was done using the equation (1). Some tests used in this section had not wave velocities acquisition (non-simultaneous tests), so the equation (1) was initially used in a reverse mode to define the expected dynamic shear modulus for the rock sample. Test confining pressure and rock measured strength are input in equation (1) and GDYN is the output for that rock sample. In the sequence equation (1) is forward applied introducing GDYN defined in the first step and the in situ confining pressure from equation (2), thus getting the in situ confining level strength as the final output. Relevant strength prediction errors may not be introduced by this procedure for confining pressures above 10 MPa, where velocities and dynamic moduli almost not change with confining pressure variation.

Another important precaution to be observed in this methodology is related to possible and very common depth shifts between core and well logs. In this work a home-made software was used to eliminate these depth shifts bringing all core sample depths to logging based depths. This software does successive fits between lab and log measured rock physical properties, defining the best lab and log data fit positioning, regarded some geological restrictions.

Figures 4a and 4b show two predicted strength logs, the former for a limestone interval and the last for a sandstone formation, assuming the vertical pressure given by equation (2) as equal to the in situ confining pressure. In these figures strength logs are given by solid lines whereas lab measured strengths, confining level corrected, are given by solid circles.

Figure 4a presents results obtained in a 200 meters limestone interval where three triaxial tests were done, only one of them being a simultaneous test and the others without P and S wave velocities acquisition (purely rock mechanics tests). In addition, four uniaxial strain tests were done in core samples from this well, for pore colapse detection. The proposed methodology provided a good match between the predicted strength log and the lab-measured strengths, regardless of test type.

A sandstone case is shown in figure 4b where the predicted strength log is compared with the core samples strength values observed in six triaxial tests.

CONCLUSIONS

The proposed methodology for continuous rock strength evaluation uses, as input variables, the dynamic shear modulus, obtained via well logging, and the in situ confining pressure, assumed here equal to the averaged overburden effective pressure. An advantage in the use of the dynamic shear modulus as input variable is that it is almost not affected by fluid saturation, being an intrinsic rock-frame mechanical property. Thus, the effect of pore fluid content can be neglected without notable prejudice for the continuous rock strength evaluation.

The simultaneous acquisition of dynamic and static rock properties had a fundamental importance in this continuous rock-strength evaluation scheme. It permits to establish the relationships between dynamic and static rock-mechanical properties, which are the basis of the methodology.

Assuming the in situ confining pressure equal to the vertical effective pressure seems have not damaged the capacity of the regression equation for log-derived rock strength evaluation. The lab-measured strengths confirm the strength logs, which were calculated using a pre-defined gradient of vertical pressure.

Nevertheless, a priori and detailed analysis of the in situ stress field for each case as well the effective acquisition of the S wave velocity log could arise the prediction capacity for this methodology.

Others factors to be considered before the application of this methodology are possible occurrence of depth shifts between core samples and well logs and do not apply the presented confining pressure level correction for pressure levels under 10 MPa.

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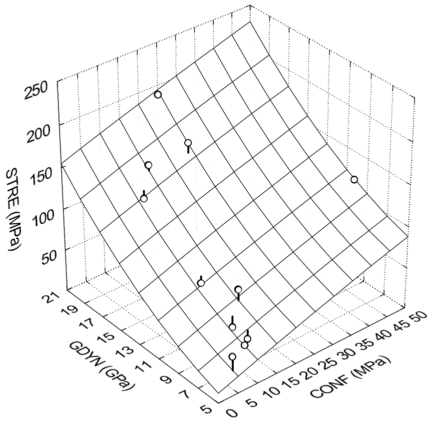


Figure 1 - Regression surface defined for limestone. Open circles indicate lab-measured values, while bars indicate prediction errors.

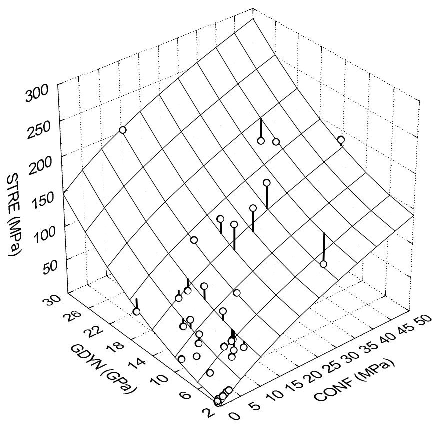


Figure 2 - Regression surface defined for sandstone. Open circles indicate lab-measured values, while bars indicate prediction errors.

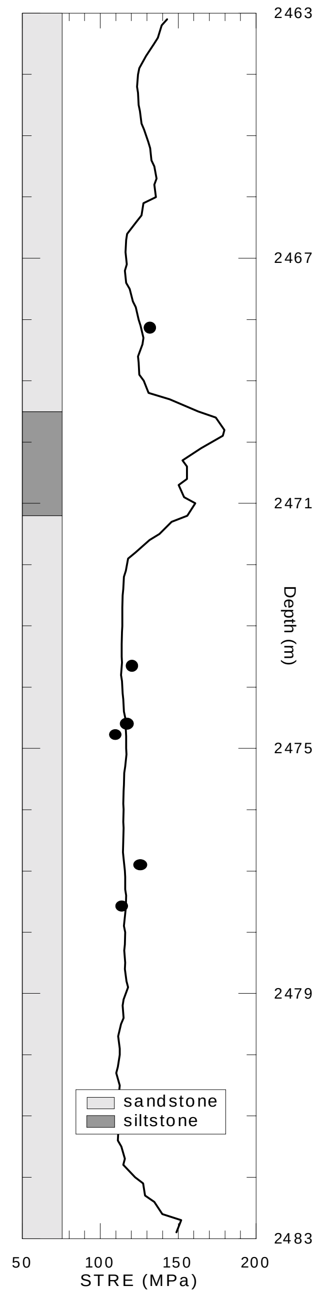
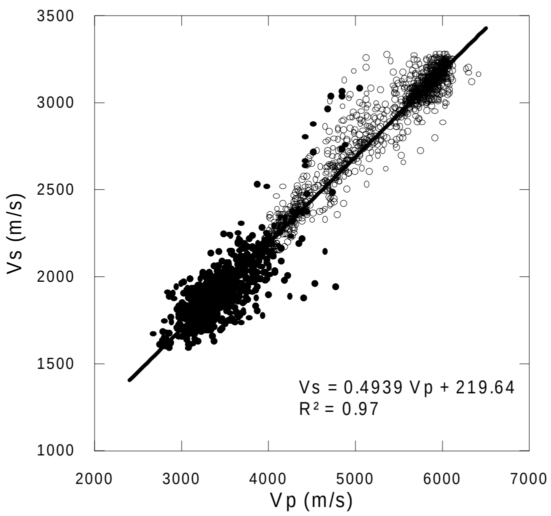
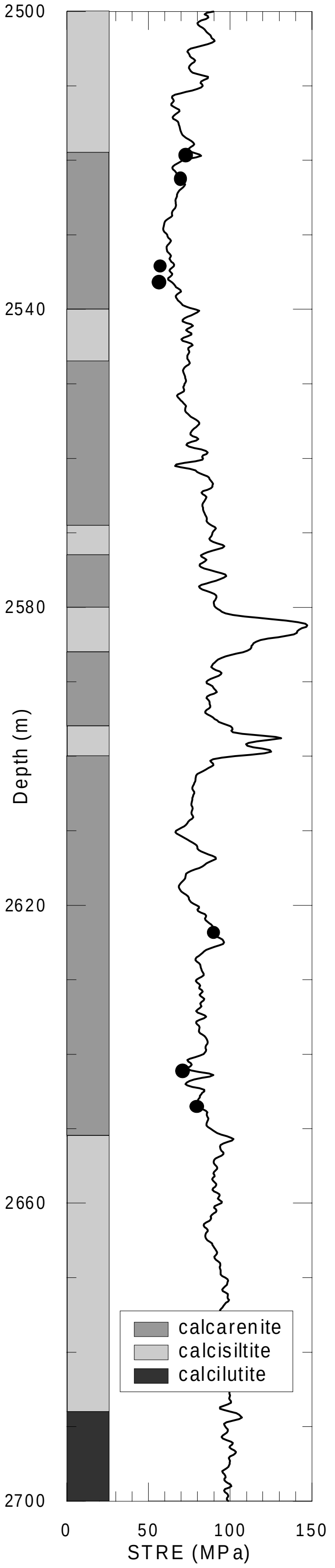


Figure 3 – Vp/Vs ratio for Vs log generation in limestone. Fit line was defined from two wells data.





(a) (b)

Figure 4 – Comparison between log-derived strength log and lab measured core strengths (solid circles) for a limestone interval (a) and a sandstone interval (b).