Pore Pressure prediction and modeling using seismic velocities

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Abstract. *Pore pressure prediction is used to develop a 3D model for the pressure regime and it is a critical property towards an effective reservoir simulation and management. A quantitative predrill prediction of pore pressure is required when drilling in overpressured formations, and can be obtained from elastic wave velocities using a velocity-to-pore-pressure transform model calibrated with laboratory measurements or offset well data. This work intends to present a methodology for 3D pore pressure prediction using a refined velocity field from seismic velocities and laboratory measurements that were developed to determine the variation between vertical effective stress and porosity at depth. Because seismic velocities correlate with effective stress in the formation, triaxial compression tests were used to assess the mechanical properties of the Codaçal limestones and the compaction trend verified from the relationship between seismic velocities and vertical effective stress.*

The main goal of this work was to build a pore pressure cube based on Eaton and Bowers pore pressure estimation models, as both Eaton's and Bowers methods uses the vertical effective stress to predict pore pressures, and compare the results obtained by the two methods. The pore pressure cube aims to support a better visualization of the mechanisms of overpressure generation and to help in a safer and economic drilling of wells.

Keywords: *Pore Pressure, effective stress, elastic wave velocities, triaxial compression test, Eaton's method, Bowers method.*

1. Introduction

Abnormal pore pressures are encountered worldwide, often resulting in drilling problems such as borehole instability, stuck pipe, lost circulation, kicks and even blowouts. Therefore the knowledge of formation pore pressure is crucial in terms of maintaining control of the wellbore and is required for the safe and economic drilling of deepwater wells. On the other hand, the overpressures are associated with the presence of hydrocarbons and their exploitation. The geopressures contribute to the sealing integrity of the reservoir, and their spatial distribution allows acquiring information about lithology, hydrogeology and flow paths.

The quantification of pressures is a challenge as there is a great difficulty in measuring pressures at depth, as well as taking cores for geomechanical tests that can help in the analysis of the stress state of the rock and the definition of overpressure generation mechanisms. Typically, the pore pressure predictions use models based on porosity and stress values from well log data that can be used with 2D or 3D seismic data. A pre-drill estimate of pore pressure can be obtained from seismic velocities using a velocity-to-pore-pressure transform calibrated from offset well data.

The pore pressure prediction using seismic velocities is based on rock physics foundations and the analysis of seismic attributes, relating physical parameters with effective stress using the Terzaghi model. Commonly is used seismic interval velocities profiles obtained from processing seismic reflection data, although often lack the spatial resolution needed to estimate the relationship between pore pressure and seismic velocity. A geomechanical model reproduces, as accurate as possible, the mechanical properties and the behavior of rock when applied external stresses. In petroleum engineering, porosity and permeability are the most relevant petrophysical properties, being also important the study of the seismic waves velocities and the strength and strain of the rocks, allowing analysis of the stability of rock formations. The physical properties control the strength and strain characteristics of the rock matrix.

The laboratory tests intended to measure simultaneously the main properties of interest (porosity, propagation of seismic waves velocities and deformability parameters) and the mechanical characterization of the geologic unit of Codaçal limestone's, through triaxial compression tests in undrained conditions. During the tests held in the elastic regime of the mechanical behavior of the rock, the following parameters were recorded: axial stress (MPa), time (s), strains and the time of seismic waves propagation (μs). This measures allowed relating the porosity and seismic wave velocities with the effective stress and pore pressure, to further develop a compaction Trend.

2. Sediment compaction

Normally, an underground formation at a certain depth supports the weight of the overlying formations. The total vertical stress (overburden stress) is the stress from all the material, either solid or fluids, at a certain depth, due to the weight of the rocks. The vertical component of the total stress (σ_v) is calculated by the weight of the rock matrix and the fluid in the pore space that overlap the range of interest. Thus, if the density (ρ) varies with depth, the total vertical stress at a given depth h is given by the equation:

$$\sigma_v(h) = g\int_0^h \rho(z)dz \qquad (1)$$

where $\rho(z)$ is the density at a certain depth below the surface and g is the acceleration of gravity. If the overlaying formations have an average sediment density of ρ_{avg} between the sea bottom and the depth of interest, then the overburden stress can be calculated from (Traugott, 1997):

$$\rho_{avg} = 16.3 + \left(\frac{d-w-a}{3125}\right)^{0.6} \qquad (2)$$

where d is true vertical depth, w water depth, a the air gap (vertical distance between kelly brushing and sea surface) and ρ_{avg} has unit of ppg. The density at the depth of interest can also be estimated from seismic velocities (V) using the Gardner's empirical relation (1974):

$$\rho = aV^{\beta} \qquad (3)$$

given the Gardner's parameters a and β. With density (g/cm^3) and velocity (m/s), typical values of a e β for Gulf Coast sediments are $a = 0.31$ and $\beta = 0.25$, (Gardner et al, 1974). Knowing the variation of density with depth and assuming a grain density (ρ_s) and a fluid density (ρ_f) the porosity may be calculated from the equation:

$$\phi = (\rho_s - \rho)/(\rho_s - \rho_f) \qquad (4)$$

The water depth must be considered in offshore for the calculation of the overburden stress, adding $\rho_w g z_w$ to (1). The conventional methods of pore pressure prediction start to build up a total vertical stress trend.

Following the deposition in the marine environment, sediments are initially unconsolidated and have high porosity and permeability. As a result, the water in the pore space is in pressure communication with the surface, and the weight of the solid phase is supported at the grain contacts and as no influence on the pressure in the fluid. The pore pressure (P_p) in the fluid is then given by the hydrostatic pressure of a column of formation water extending to the surface. Sediments in which the pore pressure is approximately equal to the hydrostatic pressure are said to be *normally pressured,* the normal pressure at depth h below the sea surface being given by:

$$P_{Normal}(h) = g\int_0^h \rho_{fluid}(z)dz \qquad (5)$$

where g is the acceleration due to gravity, and $\rho_{fluid}(z)$ is the fluid density at depth z. The sedimentary rocks at depths are porous and contain fluids; therefore part of the overburden stress is supported by the fluid pressure P_p, while the remainder is supported by the rock matrix and is referred to as the vertical effective stress (σ_v') defined by:

$$\sigma_v' = \sigma_v - P_p \qquad (6)$$

This equation defines the effective stress principle, first formulated by Terzaghi (1943), which assumes that the effective stress is given by the difference between the total stress and the pore pressure. This means that when a certain force is applied to a porous material the stress applied to the rock matrix is equal to $\sigma_v - P_p$. The deformation obtained by the stress-strain relation and the failure of the rock is controlled by the effective stress instead of total stress, therefore are the effective stresses that control the sediment compaction.

The underground stress field lay in three orthogonal principal stresses as well as in pore pressure and is normally assumed in petroleum industry that the vertical stress is a principal stress. This assumption is reasonable for great depths, in passive areas without tectonic activity. However there are exceptions, in particular near the surface, where the main stress directions are influenced by the topographic surface, or near faults, and the main stress directions will differ from the vertical-horizontal orientation. In this study it has always been considered the vertical stress as the main stress and the vertical-horizontal orientation of the stress state.

The horizontal stresses acting on an element of rock at a depth z below the surface are much more difficult to estimate than the vertical stress. Therefore it is assumed a relaxed area where the horizontal stress is induced simply as a result of the vertical stress. In a rock, the ability to resist shear stresses causes the horizontal stress (σ_h) in general to be different from the vertical stress, and the relation between both (in terms of effective stress) is:

$$\sigma_h' = K'\sigma_v' \qquad (7)$$

The ratio K' between the σ_h' and σ_v' may vary significantly and tend to be high at shallow depth and that it decreases at depth, becoming hydrostatic with time. Sheorey (1994) provided a simplified equation for estimating the relationship between the vertical and the horizontal stress:

$$K = 0.25 + 7E_h\left(0.001 + \frac{1}{z}\right) \qquad (8)$$

where z (m) is the depth below surface and E_h (GPa) is the average deformation modulus measured in a horizontal direction. Terzaghi and Richart (1952) suggested that, for a gravitationally loaded rock mass in which no lateral strain was permitted during formation of the overlying strata, the value of K is independent of depth and is given from the Poisson's ratio:

$$K = \frac{\nu}{(1-\nu)} \qquad (9)$$

Traugott (1997) proposed an empirical equation to determine the relationship between the horizontal and vertical stress as a function of depth by:

$$K = 0.039\left(\frac{z}{0.305}\right)^{0.33} \qquad (10)$$

3. Pore pressure

The pore pressure (P_p) may also be referred to as formation pressure and is the fluid pressure within the pores of a soil or rock. Without a proper input of the pore pressure an adjusted prediction becomes impossible to obtain for any geomechanical model.

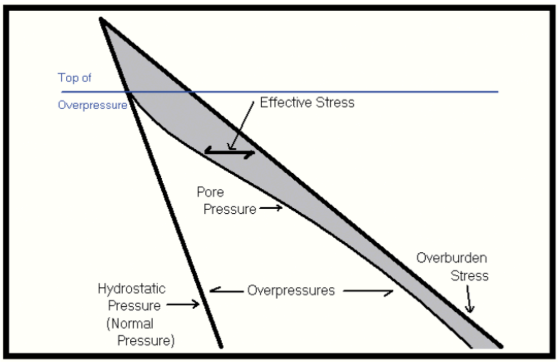

Figure 1 – Pressure plotted against depth. Overpressure is the amount of P_p in excess of hydrostatic pressure (Bruce&Bowers, 2002).

The pore pressure develops into a saturated formation as the sediment is buried to greater and greater depth in a marine environment. The weight of the overlying rocks increase, and the increasing stress acting at the grain contacts leads to rearrangement of the grains, resulting in lower porosity and permeability. If the rate of sedimentation is similar to the rate at which fluid can be expelled from the pore space is maintained a normal pore pressure gradient. Whereas if the rate of sedimentation exceeds the rate of fluid expelling, or if dewatering is inhibited by the formation of seals during burial, the pore fluid becomes overpressured and thus supports part of the overburden load. Overpressure generated in this way is said to result from disequilibrium compaction or undercompaction, this being the most common mechanism for generating overpressure in deepwater sediments. The pore pressure may be measured by direct methods, common in permeable layers, or by indirect methods through the interpretation of drilling parameters, logs and seismic profiles.

Formation pore pressure is divided into the three categories normal, abnormal and subnormal formation pressure. The term normal pressure describes the situation where formation pressure is approximately equal to the theoretical hydrostatic pressure. Abnormal (or overpressure) and subnormal pressures represent pressures of respectively higher or lower values than this normal situation. The overpressure may have three causes: related to stress mechanisms (disequilibrium compaction or tectonic mechanisms); increment of fluid volume (chemical or thermal processes); and flow of hydrocarbon fluids. Each mechanisms that produces overpressures causes different porosity values, so P_p prediction must be performed on the basis of the mechanisms that produced it.

4. Pore pressure prediction

The pore pressure prediction methods have been developed in the recent decades and many of them are based on the effective stress principle. Most of these methods are empirical approaches that use data from logs, seismic profiles and porosity determinations.

The traditional pore pressure prediction methods are supported in relations between porosity, pore pressure and effective stress and only take into account the undercompaction mechanism as the cause of overpressure, which can lead to significant errors. The traditional methods equate departures from the trend line of some porosity-dependent measurement to an equivalent P_p gradient and do not always provide reasonable results due to the lack of data in the input or an inappropriate definition of the overpressure generating mechanism.

The pore pressure estimation methods can be classified into three groups: methods based on sedimentary basins models; methods using seismic data, empirical models and rock physics models; methods that use logs data to generate rock physics models. This study examined the integration of experimental data with seismic data in the same framework.

The first pore pressure estimation methods correlated empirically log data with pore pressure measurements, such as the equivalent depth method (Foster&Whalen, 1966). The pioneering work by Pennebaker (1968) was the first method that used seismic data for pore pressure analysis. This method employ interval velocities derived using the Dix equation.

The pore pressure estimation from seismic velocities is based on the analysis of seismic attributes: wave speed, transit time, the amplitude, the reflection coefficients and the impedance. The seismic velocities in rocks increase during compaction due to porosity reducing. Since any increasing in P_p above the normal hydrostatic gradient reduces the amount of compaction that occurs, the seismic velocity can be used to P_p prediction.

If the relation between elastic wave velocity and vertical effective stress is known, the P_p may be calculated. Examples of the use of vertical effective stress to predict P_p include the methods of Eaton (1975) and Bowers (1995), the two methods used in this study. Eaton (1975) proposed an empirical method correlating the physical parameters of the geological layer with the vertical effective stress and using the Terzaghi model (1943). The Eaton’s method is based on the undercompaction mechanism and the relation between the effective stresses in abnormal and normal compaction conditions, and is the most widely used in the oil and gas industry. In this method the pore pressure at a given depth is a function of the overburden stress, the hydrostatic pressure, the ratio between the observed parameter and the value of the compaction trend.

The Eaton´s method starts to plot the compaction trend in normal conditions from the physical properties that are restricted, directly or indirectly, by the porosity. This trend represents the normal conditions of compactions with the increasing of overburden stress. The overburden stress is a function of depth and is calculated from density logs or using the Traugott’s equation (1997) or the empirical relationship from Gardner et al. (1974). To use these equations is necessary to know the relationship between the elastic wave velocities and the vertical effective stress. Through Eaton’s method can be estimated the vertical component of the effective stress from seismic velocities by the relationship:

$$\sigma'_v = \sigma'_{Normal} \left(\frac{V}{V_{Normal}}\right)^n \quad (11)$$

where σ'_{Normal} and V_{Normal} are the vertical effective stress and the seismic velocity expected if the sediment is normally pressured, while n is an exponent that describes the sensitivity of velocity to effective stress. The pore pressure is then given by:

$$P_p = \sigma_v - (\sigma_v - P_{Normal}) \left(\frac{V}{V_{Normal}}\right)^n \quad (12)$$

σ_v is the overburden stress, P_{Normal} the normal pore pressure, V the seismic velocity and V_{Normal} the normal seismic velocity. The exponent n can be adjusted from well data or may be kept fixed the value 3.

To use Eaton's method, the deviation of the measured velocity from that of normally pressured sediments must be estimated. As Eaton said, the power of the pore pressure results using his method depends of the data quality and the individual evaluation by the pore pressure technician in carrying out the compaction trend.

The method proposed by Bowers (1995) is an effective stress approach; the effective stress is computed from the velocity and the result is subtracted from the overburden stress to obtain the P_p. This method accounts for excess pore pressure generated by both undercompaction and fluid expansion mechanisms and presents two models, each corresponding to the respective generating mechanism. To include multiple sources of overpressure, a pair of velocity-to-effective stress relations are introduced. In this study we only considered the undercompaction mechanism, related to the non-decreasing effective stress state. In this state, under increasing effective pressure, sediments compact, and their sonic velocity goes up. The velocity-effective stress relations for non-decreasing effective stress is referred to as the *virgin curve*. According to Bowers (1995), undercompaction is normally the mechanism that causes overpressure at shallower depths, where the formations are soft, and the fluid expansion is the mechanism that generates overpressure at deeper depths, in stiffer rocks. The method of Bowers is an effective stress approach that in the undercompaction mechanism defined the *virgin* curve relation:

$$V = V_0 + A\sigma'^B \quad (13)$$

where V is the velocity, V_0 is the velocity of sediments at the seafloor, σ' is the effective stress, and A and B are the parameters calibrated with velocity-to-effective-stress data.

The two fundamental bases for the overpressure predictions methods from seismic velocities are the variations of interval velocities in geological formations and the variations of amplitudes of seismic wave reflections. Overall, it should be known the way seismic data were acquired, processed and interpreted. The velocity-to-pore-pressure transform must be calibrated with offset well data and the density data must be integrated to determine the effective stress variation with depth. This paper demonstrates that these parameters can also be obtained through laboratory testing and without the need of pre-existing pressure data. In order to do this calibration, it can be used a parameterized expression for V_{Normal}. There are several analytical expressions describing the variation of seismic velocity with depth, but the most commonly used is the Slotnick's expression:

$$V_{Normal}(z) = V_0 + kz \quad (14)$$

where z is the depth measured from the seafloor and V_0 is the velocity of sediments at the seafloor. Typical values of the vertical velocity gradient k lie in the range 0.6 to 1 s^{-1}.

The pore pressure prediction from seismic velocities requires the knowledge of the parameters V_0, k and the Eaton's exponent n, for the Eaton method, and the parameters A and B for the method of Bowers.

5. Experimental procedure

To achieve the goals of this study were developed laboratory tests that exposed rock specimens to the variations of triaxial stress states, measuring simultaneously the main properties of interest in mechanical characterization. Twenty-five specimens (40 mm diameter and 84 mm length) from the Codaçal Limestone's formation (Bathonian) were tested accordingly to ISRM procedures at IST's Geomechanics Laboratory. The properties of interest were the porosity, the propagation of seismic wave velocities and the deformability parameters (E and ν), at each triaxial stress state applied.

Figure 2 – Apparatus for the triaxial rock test with stress, strain, P-wave and S-wave measurements.

For testing, Hoek triaxial cell (fitted to cylindrical specimens) were used, allowing the application of two principal boundary stresses independently. Axial and radial strains were measured directly on the sample using strain gauges, which were mounted in a quarter Wheatstone bridge (strain measurements accuracy was close to 10^{-6}) and the correspondent registration's equipment – Strain Register and Recorder allowed data recorded.

P-wave and S-wave velocities were measured parallel to the major axis, along diameters of the sample, using a pair of source-receiver piezoceramic (PZT) transducers for each velocity, connected to a pulse generator and receiver at frequencies of 55 kHz. The sensors were installed on the loading pistons of the triaxial cell and were developed from scratch for this work.

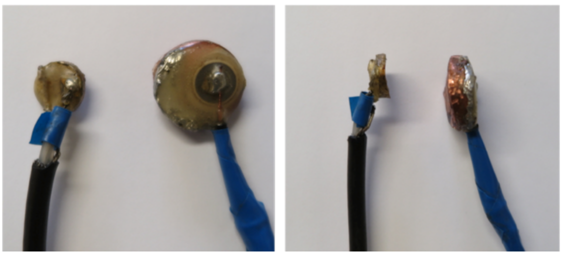

Figure 3 – P-wave and S-wave transducers.

Because of the technical difficulty of using all the transducers in simultaneous recording, were performed two cycles (followed by charge-discharge) in each specimen, using the P-wave and the S-wave transducers in each cycle. This methodology was possible due to the fact that triaxial tests were always conducted in the elastic regime of the material.

For each test, a hydrostatic stress state was obtained in order to start the triaxial test and then the axial stress was increased until the predefined value was reached, keeping confining pressure constant. Four specimens were tested for each confining pressure, 0.5, 1.0, 2.0, 4.0, 8.0 and 16.0 MPa. All the triaxial tests were carried out at a constant load rate (0.5 MPa/s), accordingly to ISRM suggested method.

6. Results

In this section, the evolution of the elastic properties of samples during triaxial tests (axial loading increasing), for different confining pressures are presented. The studied properties were: deformability parameters (Young's modulus and Poisson's ratio), P-wave and S-wave velocities and porosity reductions. The results obtained in triaxial tests correspond to the evolution of physical and mechanical properties of Codaçal limestones. The convention that compressive stresses and compactive strains are positive, like traditionally is applied in rock mechanics, was adopted. The confining pressure is designated P_c, in all triaxial tests $P_c = \sigma_2 = \sigma_3$ and the applied terms *axial* and *transverse* refer to the position of the specimens in the triaxial cell.

The increasing of velocity of the seismic wave propagation as it increases the axial stress is related to the compaction of the rock specimen during the triaxial test and the decreasing of porosity and increasing of pore pressure. As expected, the velocity of P-wave propagation, between 2000 and 3000 m/s, is greater than the velocity of S-wave propagation, between 1500 and 2500 m/s.

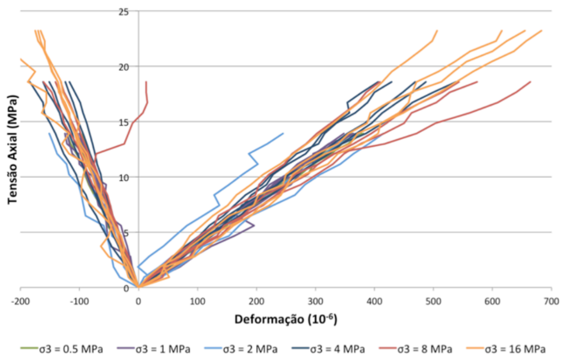

Figure 4 – Stress vs. strain curves.

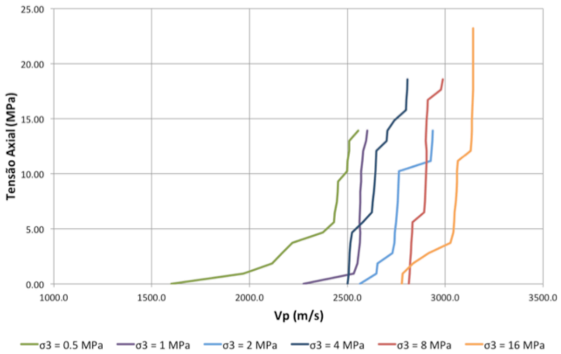

Figure 5 – P-wave velocity variations with axial stress increasing.

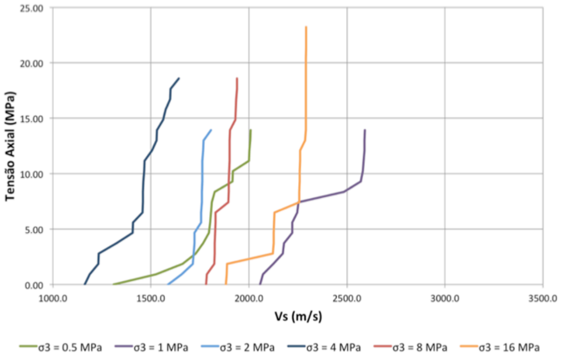

Figure 6 – S-wave velocity variations with axial stress increasing.

The greater variability in the velocity measurements of S-wave propagation arise from the fact that the S-waves depend on several parameters that vary depending on the tests conditions.

The porosity reduction ($\%\Delta\phi$) was calculated from the previous values of strain according to the equation:

$$\%\Delta\phi = \frac{\Delta\varepsilon_{vol}}{V_t} = \frac{\Delta\varepsilon_a + 2\Delta\varepsilon_t}{V_t} \quad (15)$$

where ε_{vol} represents the volumetroc strain, V_t is the total volume (m3), ε_a is the axial strain and ε_t is the radial strain.

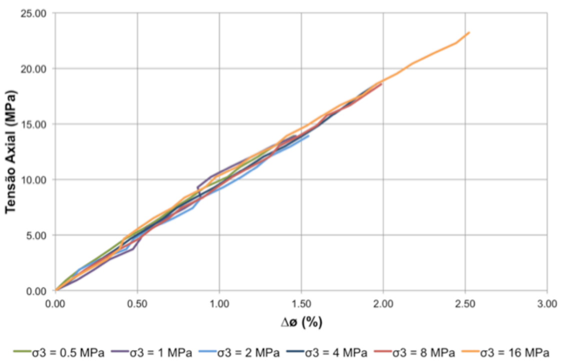

Figure 7 – Porosity reduction variations.

The results of porosity reduction variations show a similar behavior and a constant rate of porosity reduction with axial stress increasing in all confining pressure.

The static deformability parameters (E and ν) were determined from the strains and the axial stress applied.

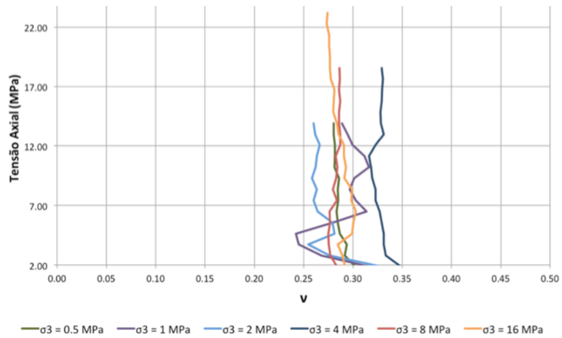

Figure 8 – Poisson's ratio variations.

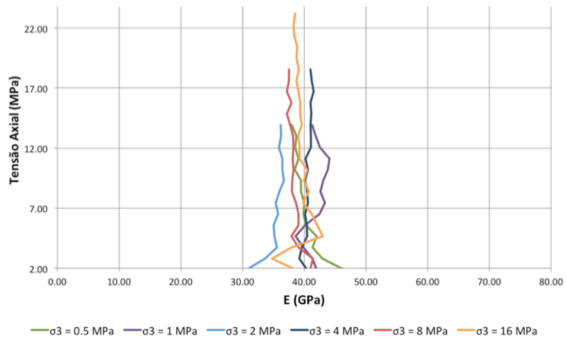

Figure 9 – Young's modulus variation.

The Poisson's ratio shows a relatively similar behavior in all confining pressures, with values between 0.25 and 0.30. The exception occurs at confining pressure of 4 MPa ($\nu = 0.33$) with irregular behavior.

The Young's modulus, with values between 35 and 41 GPa, had a consistent performance between the different confining pressures, except at $P_c = 1$ MPa with irregular behavior.

The Lamé's parameters, λ and μ, are elastic moduli, μ is also known as the shear modulus.

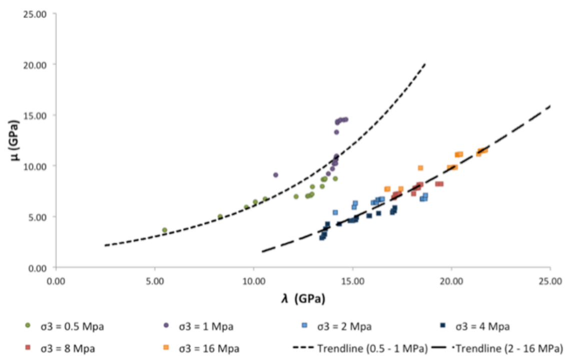

Figure 10 – Elastic behavior trends.

Both parameters can be calculated from the velocity of seismic wave propagation and density values. From the relationship between both parameters, it was found that there are two elastic behavior trends depending on the stress state, a trend to lower confining pressures (0.5 and 1 MPa) with higher values of μ, and a trend to higher pressures (2, 4, 8 and 16 MPa) with lower values of μ.

For a more thorough evaluation of the mechanical behavior of the Codaçal limestone's we proceeded to an analysis from empirical relationships already proposed by other authors, verifying the level of compatibility between them and the results obtained in the laboratory tests. We also developed some relations between the most important parameters in this study in order to define one trend between them. The parameters that were analyzed were the velocity of seismic wave propagation, the density, the porosity, the Poisson's ratio and the effective stress.

The following linear relation represents the trend of effective porosity with depth, where z is the depth:

$$\phi = 0.1239 - 2\times10^{-5}z \qquad (16)$$

Also developed was the trend of porosity variation with the increasing of vertical effective stress (σ_v'), defined by the linear relation:

$$\phi = 0.1236 - 0.0019\sigma_v' \qquad (17)$$

In order to use in models based on seismic velocities, the trend of porosity variation with velocity of P-wave propagation (km/s) was set:

$$\phi = 0.1901 - 0.03V_p \qquad (18)$$

It was determined the trend of density variation with depth, defined the density of the rock matrix as 2.305 g/cm^3 and the density of the pore space fluid in the specimens as 1.00 g/cm^3. In this analysis was also made a comparison between the results obtained in the laboratory tests and the Traugott's model. It was concluded that the Traugott's model induces errors by default in the results, especially in shallow depths. The laboratory results produced a trend of density (g/cm^3) variation with depth represented by a linear relationship:

$$\rho = 2.1433 + 3\times10^{-5}z \qquad (19)$$

The analysis of the relationship between the density and the velocity of P-wave propagation was performed by comparing the laboratory results with empirical relationships proposed by the Nafe-Drake's equation and the Gardner's equation for crustal rocks.

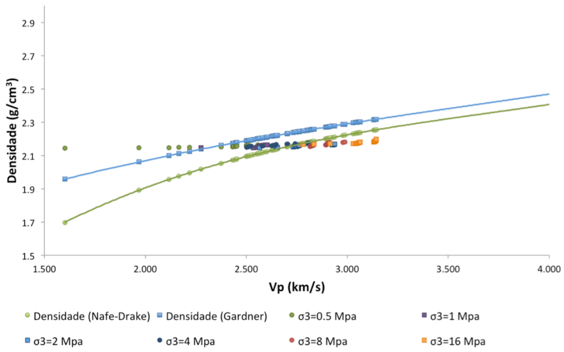

Figure 11 – The analysis between density and velocity of P-wave propagation.

There is a good fit of the laboratory results on the empirical relationships, significantly better on the Nafe-Drake's equation, especially at higher confining pressures.

It was developed from the Gardner's equation the empirical relationship between the density and P-wave velocity for Codaçal limestone's between the confining pressures of 2 to 16 MPa:

$$\rho = 2.0043V_p^{0.0749} \qquad (20)$$

The $V_p - V_s$ relations are fundamental to be able to determine the lithology form seismic data and for a seismic direct identification of pore fluids. There is a wide variety of $V_p - V_s$ relations that established empirical relations between V_p, V_s and porosity for a given pore fluid. An analysis of the relationship between the velocity of P-wave and S-wave propagation was made using empirical relationship developed by Brocher (2005), Pickett (1963) and Castagna et al. (1993), comparing with the laboratory results.

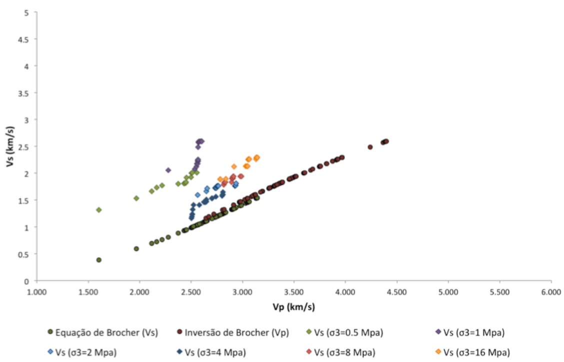

Figure 12 – Brocher's $V_p - V_s$ relations for crustal rocks and laboratory results.

This analysis verified, as explained previously, two distinct trends, one for lower confining pressures (0.5 and 1 MPa) and other to higher confining pressures (2 to 16 MPa) and closer to the relationships proposed by Brocher.
Pickett (1963) and Castagna et al. (1963) developed empirical $V_p - V_s$ relationships from lab ultrasonic data to saturated limestones. In figure 13 we can see again the same distinct trends as before.

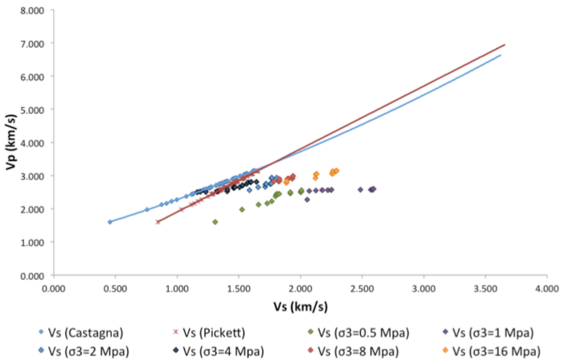

Figure 13 – $V_p - V_s$ relations for limestones.

In the definition of the stress state in depth, it has proved extremely important the definition of the ratio between the horizontal and vertical stress (K) prior to the development of normal compaction models and the relation between vertical effective stresses and seismic wave velocities. For the calculations of the K ratio, it was used elastic models and empirical relationship proposed by some authors (Sheorey, Terzaghi & Richart and Traugott), compared the results between them and defined what relationship best suited to the laboratory results. After determining the K ratio from each model and for each P_c, the values of horizontal stress were calculated associating them with the vertical stress. The model of Sheorey wasn't suited to the lab results obtained.
From the relationships obtained from the Terzaghi & Richart and Traugott models were developed models of the variation of P-wave and S-wave velocities in depth. The V_p vs. Depth models are important to define the normal compaction trends needed to pore pressure prediction by Eaton method. The V_p vs. Depth models for the lab results using the Terzaghi & Richart and Traugott models were, respectively:

$$V_{Normal} = 2054.5 + 0.9261z \qquad (21)$$

$$V_{Normal} = 2081.2 + 0.9711z \qquad (22)$$

The Traugott model presented the best fit to the lab results so the equation 22 was the equation used in the pore pressure estimation.
It's also important to define the V_p vs. effective stress trends for normal compaction conditions. Therefore, were developed V_p vs. effective stress trends based on the Terzaghi & Richart and Traugott models. It was found that the Traugott model presented a better fit to the lab results. The V_p vs. effective stress trends from Bowers equation for the Terzaghi & Richart and Traugott models were also defined, although only the equation 24 (Traugott model) was used in the pore pressure estimation:

$$V_{Normal} = 1632 + 638\ {\sigma_v'}^{0.2308} \qquad (23)$$

$$V_{Normal} = 1976 + 326.3\ {\sigma_v'}^{0.3646} \qquad (24)$$

To pore pressure estimation from seismic velocities, was used a synthetic P-wave velocity cube (Pinto, 2014) developed for a carbonated sedimentary basin.

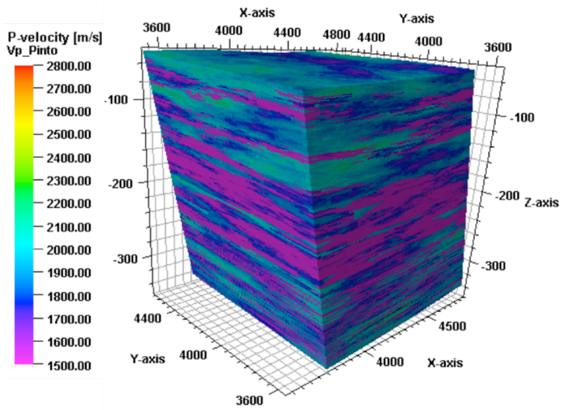

Figure 14 – P-wave velocity cube (Pinto, 2014).

Taking into account the dimensions of the cube (161x161x300 cells, 25x25x1 m per cell) and using the analysis between the seismic velocities, the physical and mechanical parameters and the vertical effective stresses, were modeled for the same area, for normal compaction conditions, the overburden stress, the hydrostatic pressure, the porosity, the vertical effective stress and the density. From these 3D models it was developed a 3D V_p model in normal compaction conditions using the Bowers equation developed for the Codaçal limestones.

Finally, pore pressure models were developed using the Eaton and Bowers methods, the synthetic P-wave velocity cube and the analysis from the lab results developed in this paper. It was found that the Eaton method tends to underestimate the pore pressure compared with the Bowers method, being very important the lithology in which they are used.

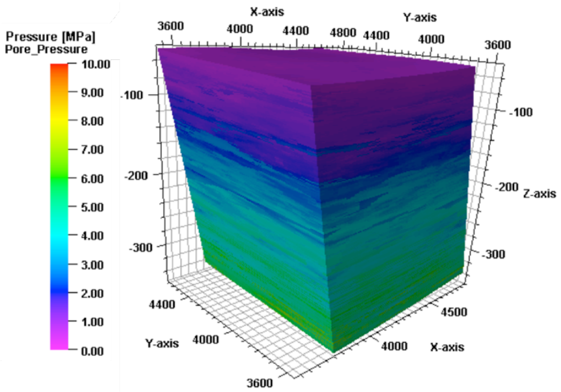

Figure 15 – Pore pressure prediction using the Eaton method.

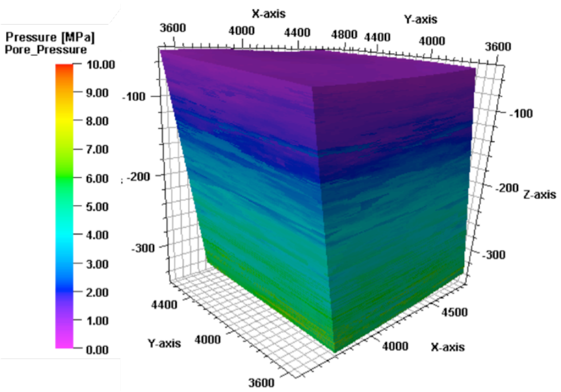

Figure 16 – Pore pressure prediction using the Bowers method.

7. Conclusion

The pre-drill pore pressure estimation use surface seismic data to estimate the seismic velocities and set the velocity-to-effective-stress transform for a given area, then combining the overburden stress to estimate the P_p. This paper aims to present a methodology to develop this transform from laboratory tests, carrying out an analysis of this relationship at different confining pressures and overburden stresses on hydrostatic conditions. By comparing the laboratory results with empirical relationships from other authors it was possible to carry out a qualitative and quantitative analysis of the proposed methodology, verifying a better fit of the data to the greater stress state. From the analysis of the strength and strain parameters of lab results it was found distinct trends between lower and higher confining pressures.

Using the Eaton method and the Bowers method, it was concluded that although the Eaton method is more directly applicable and relatively quick, the compaction trend dependence is huge and can induce underestimated P_p estimations. On the other hand, the Bowers method has a higher sensitivity in P_p estimation from seismic velocities as it applies to a relation between seismic velocity and vertical effective stress.

Finally, it is concluded that this methodology, using triaxial tests, enables a more robust approach to P_p prediction and developed a more direct analysis of the physical and mechanical characteristics that influence the P_p of a given geologic unit, and may be used with significant precision in a relatively large area if developed compaction trends to each geological formation.

8. References

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