Continuous Dry Bulk Density Evaluation Using Borehole Magnetic Resonance and Density Measurements

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SUMMARY

Dry bulk density is a key parameter in resource estimation and mine and process planning. Ore bodies are mapped as volumes, whereas mineralisation grade is reported as mass fractions, requiring rock density to complete the reserves calculation. Similarly, although a volume of rock is to be excavated, planning for the transport and processing of this material takes place in terms of the mass of ore to be handled, again requiring rock density information to convert between the two.

Although many different densities can be defined based on the underlying mass and volume definitions, the one of most interest to the mining industry is dry bulk density, or the dry mass per unit volume of in-situ rock. This contrasts with the in-situ bulk density, which includes the mass of any fluids in the pore space of the rock. In-situ bulk density can be accurately measured using borehole geophysical techniques, but no direct downhole measurement of dry bulk density is possible. Therefore, common practice is to determine mass, after drying, and volume of core samples for calculation of dry bulk density. However, this process can be time consuming and problematic with porous or unconsolidated samples.

Another approach to estimate dry bulk density, amenable to downhole application and therefore avoiding many of the complications related to core measurements, utilises in-situ bulk density and magnetic resonance porosity measurements. Combining these two measurements allows for continuous dry bulk density evaluation without the need for coring.

Key words: dry bulk density, magnetic resonance, well logging.

INTRODUCTION

Density is a key input to both mineral resource evaluation and mine planning. Mineral resource estimates are determined as the product of ore body volume, ore grade, and density. Planning for ore handling in transportation and processing involves estimates masses of rock to be handled; this again is determined as the product of rock volume and density.

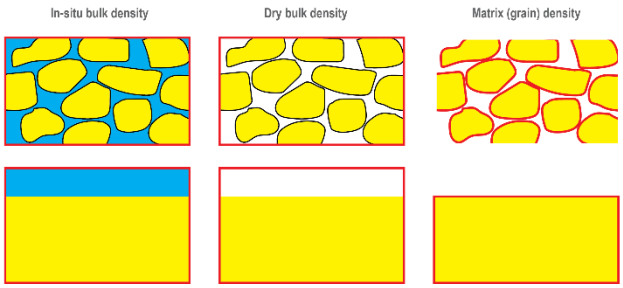

Figure 1: Graphical representation of in-situ bulk density, dry bulk density, and matrix (grain) density definitions. Yellow represents rock matrix and blue represents associated fluids. Coloured formation components indicate masses included in density definition. Red border indicates volume included in density definition.

Density is most simply defined as the ratio of the mass of a material to the volume it occupies. However, in the mining industry, several different densities are employed depending on the selection of masses and volumes to be included (Abzalov, 2016; Lipton and Horton, 2014). The most direct is the in-situ bulk density, defined as the mass of a rock, including contained fluid, to the bulk volume occupied by the rock matrix and associated porosity with contained fluids. This is of interest in mine planning, for estimation of tonnages of rock to be transported or processed. A second, and equally important, density measure is the dry bulk density, defined as the mass of the dry rock framework to the bulk volume occupied by the rock matrix and associated porosity. The dry bulk density is used in resource assessment to relate ore grades, measured on a mass fraction basis, to ore body volume. A third density measure is the matrix or grain density, defined as the mass of the dry rock framework to the volume occupied by the dry rock framework.

Density is typically measured on core samples obtained from boreholes drilled to evaluate an ore body and surrounding country rock. Density is determined by independently measuring mass and volume. Mass is generally trivial to evaluate, although in the case of dry bulk density the mass is determined on a sample after it is dried; achieving entirely moisture-free samples prior to weighing can be time-consuming and difficult to quality control. Volume can be significantly more problematic to evaluate. For dry bulk density, the bulk volume of the rock, including associated pore space, must be determined. For small, regularly-shaped samples, this can be done through direct measurement of sample dimensions. Sample volume can also be determined by volumetric or buoyancy displacement methods, although porous samples require special handling to ensure that fluid does not penetrate the pore space of the samples,

reducing the apparent bulk volume. For larger samples, such as entire core trays, the common approach is to assume the core is cylindrical with dimensions of nominal core diameter and length of core in the core tray. This assumes full core recovery, although it is applicable to highly damaged or fragmented core so long as this assumption is valid. For matrix density, the volume of grains is determined by disaggregating or crushing the sample, and then measuring the volume of the resultant material through displacement or gas expansion techniques.
These methods are quite labour-intensive, and their manual nature leaves them open to potential sources of error. There is also a need to ensure full drying of the samples prior to measurement, which in the case of large samples can take significant time and be difficult to quality control. It is easier to make accurate density measurements on smaller samples, but these are potentially less representative of overall density variations in a rock mass of interest.

Borehole geophysical measurements provide a means to continuously evaluate the rocks intersected by boreholes. One of the most common geophysical well logs employed is bulk (gamma-gamma) density. This uses the attenuation of gamma rays as they travel from a gamma ray source to gamma ray detectors to evaluate the density of the intervening material. This is necessarily the in-situ bulk density, as it includes the effect of all components in the rock being measured. No direct downhole measurement of dry bulk density is possible. However, as will be shown below, if water content can be determined using another method, then dry bulk density can be estimated from in-situ bulk density and water content. Borehole magnetic resonance is another borehole geophysical measurement that directly measures water content, and so in combination with bulk (gamma-gamma) density measurements allows dry bulk density and other density measures to be evaluated.

BOREHOLE MAGNETIC RESONANCE

Borehole magnetic resonance (BMR) takes advantage of interactions between hydrogen nuclei and applied (electro)magnetic fields. Hydrogen nuclei possess both angular momentum and a magnetic moment; simplistically they behave like magnets spinning around their magnetic axes. The rate at which the nuclei spin is a function of the magnetic field strength they are exposed to. In a volume of water, or other hydrogen-containing fluids, the magnetic fields of the various hydrogen nuclei in the different fluid molecules will be randomly oriented. If an external magnetic field is introduced, these nuclei will align themselves with the external magnetic field, or polarise. If the effect of this external magnetic field is then removed, the nuclei will over time dephase, until they are again randomly oriented.

A magnetic resonance measurement consists of two steps (**Error! Reference source not found.**). In the first step, an external magnetic field B0 is introduced for a certain period, the wait time or polarisation time. During this period, the hydrogen nuclei align with the B0 field. In the second step, the effect of the external magnetic field is removed. In practice, this is done by applying an electromagnetic pulse at a frequency in resonance with the spin rate of the hydrogen nuclei, tipping the nuclei through 90° into the secondary B1 field plane. As well as effectively removing the influence of the B0 field, this also results in the tipped hydrogen nuclei rotating around the B0 direction and perpendicular to their magnetic axes, or precessing. The precessing hydrogen nuclei generate an oscillating electromagnetic field that can be detected. This rotation rate is governed by the initial spin rate of the nuclei, which is governed in turn by the B0 field strength.

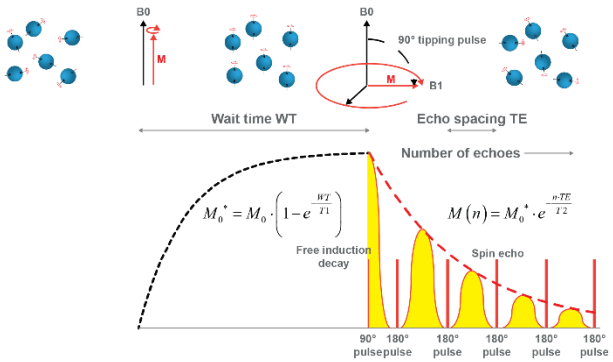

Figure 2: Making a magnetic resonance measurement. Spinning hydrogen nuclei polarise under the influence of an external magnetic field B0, and dephase when the influence of this magnetic field is removed; this is achieved by tipping the nuclei through 90° into the B1 plane using a resonant frequency electromagnetic pulse. While rotating in the B1 plane, the hydrogen nuclei in turn generate an oscillating electromagnetic signal that is measured. Polarisation and dephasing are quasi-exponential processes characterised by time constants T1 and T2.

When all the hydrogen nuclei are precessing in alignment, a peak electromagnetic signal is generated. However, due to local heterogeneities in the B0 field, nuclei will precess at different rates and hence quickly dephase, causing a reduction in the net electromagnetic signal. This process, known as free induction decay, is an experimental artefact and is reversible. Applying an appropriate electromagnetic pulse will tip the nuclei by 180°, effectively reversing the direction of rotation. This will bring the faster and slower precessing nuclei back into alignment, causing a new peak signal, or spin echo, to be generated. By applying a series of 180° pulses at a regular interval, or echo spacing, the precessing nuclei can be continually refocussed.

While this is taking place, the hydrogen nuclei are also undergoing irreversible dephasing; this has the effect of moving the axis of rotation of the nuclei out of the B0 direction so that they no longer contribute to the measured signal. Therefore, over time the amplitude of the spin echoes reduces as nuclei undergo irreversible dephasing. Both polarisation and dephasing of the hydrogen nuclei are quasi-exponential processes, with the rate of polarisation described by the longitudinal relaxation time T1 and the rate of dephasing described by the transverse relaxation time T2. The rates at which polarisation and dephasing take place are controlled by interactions between the magnetic fields of the hydrogen nuclei and other local magnetic fields (Figure 3); this includes interactions with the magnetic fields of other hydrogen nuclei in the fluids, known as bulk relaxation, and interactions with magnetic fields generated by paramagnetic atoms such as iron and manganese that may occur in the minerals bounding fluid-containing pores in a rock, known as surface relaxation. Another contributor to dephasing is diffusional relaxation, which takes place when fluid molecules move to areas of differing magnetic

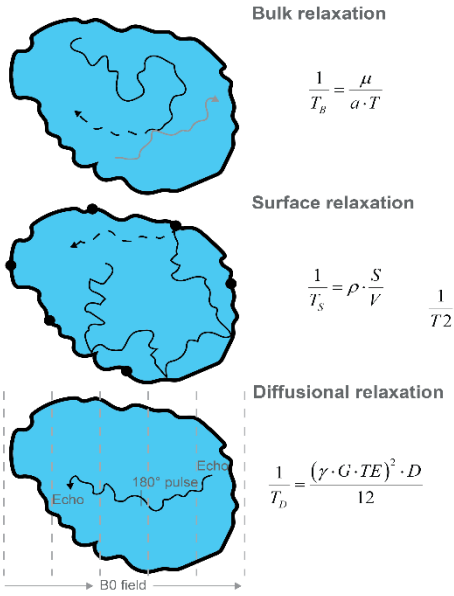

Figure 3: Polarisation (longitudinal relaxation) and dephasing (transverse relaxation) involve two processes, bulk and surface relaxation, occurring in parallel. Dephasing is additionally influenced by diffusional relaxation.

field strength during a magnetic resonance measurement, and are therefore not refocussed successfully by applied 180° pulses. Each of these relaxation mechanisms operates in parallel, and so the overall relaxation rate is dominated by the fastest mechanism.

DENSITY ESTIMATION

The peak electromagnetic signal generated at the beginning of the dephasing process is a direct measure of the amount of hydrogen in the rock that is free to polarise under the influence of the externally applied magnetic field. This includes hydrogen in fluids such as water, but does not include hydrogen forming part of a crystalline mineral structure, such as hydrogen in hydroxyl groups in clay minerals, or water of hydration in gypsum, or in solid hydrocarbon molecules, such as hydrogen in the solid components of coal. The magnitude of this signal is also independent of lithology or mineralogy. Tool calibration relates this signal to the response of the tool in 100% water, directly relating this response to water-filled porosity.

The direct, lithology-independent estimate of water content derived from borehole magnetic resonance measurements can be combined with bulk (gamma-gamma) density measurements to determine a variety of different density estimates. These all result from combination of the borehole magnetic resonance and bulk density response equations, expressed in terms of the volumes of rock matrix and fluids in the rock. For the most general case, we will consider pore space containing both water and air.

$$\rho_b = V_{ma} \cdot \rho_{ma} + V_w \cdot \rho_w + V_a \cdot \rho_a$$
$$\phi_{BMR} = V_w \cdot \phi_{BMR_w}$$

In these equations, ρ_b (bulk density, g/cm^3) and ϕ_{BMR} (BMR porosity, 1) are the overall tool responses, V_{ma} (volume of matrix, 1), V_w (volume of water, 1), and V_a (volume of air, 1) are the volumes of the components making up the formation, and ρ_{ma} (density of rock matrix, g/cm^3), ρ_w (density of water, g/cm^3),ρ_a (density of air, g/cm^3), and ϕ_{BMR_w} (BMR porosity response in water, 1) are the tool responses to the different formation components.

Considering first the case of dry bulk density, the mass and volume of a unit volume of material can be defined as follows, assuming the mass of air in the pore space of a partially unsaturated sample is negligible, the same assumption made in the measurement of dry bulk density on core samples.

$$Mass = V_{ma} \cdot \rho_{ma} = \rho_b - V_w \cdot \rho_w - V_a \cdot \rho_a = \rho_b - \frac{\phi_{BMR}}{\phi_{BMR_w}} \cdot \rho_w$$
$$Volume = V_{ma} + V_w + V_a = 1$$

Combining these, and recognising that the BMR porosity response in 100% water is 100%, the dry bulk density ρ_{db} (g/cm^3) is given by:

$$\rho_{db} = \rho_b - \phi_{BMR} \cdot \rho_w$$

With little loss of accuracy, the density of water can be assumed to be equal to 1 g/cm^3, although more accurate results can be obtained estimating water density as a function of salinity and temperature. This method allows to derive a continuous dry bulk density estimate for resource estimation.

Considering now the case of matrix density:

$$Mass = V_{ma} \cdot \rho_{ma} = \rho_b - V_w \cdot \rho_w - V_a \cdot \rho_a = \rho_b - \frac{\phi_{BMR}}{\phi_{BMR_w}} \cdot \rho_w$$
$$Volume = V_{ma} = 1 - V_w - V_a$$

Although it is possible to assume the mass of air in a partially unsaturated sample is negligible, the volume must be considered. Combining there leads to the following formulation for matrix density ρ_{ma} (g/cm^3):

$$\rho_{ma} = \frac{\rho_b - \phi_{BMR} \cdot \rho_w}{1 - \phi_{BMR} - V_a}$$

If the formation is fully water-saturated, the air volume term is zero and therefore matrix density can be determined from the combination of bulk density and borehole magnetic resonance data. However, if the formation is partially saturated, it is not possible to determine matrix density directly using this method.

An additional benefit of the sensitivity of borehole magnetic resonance measurements to pore geometry, as well as pore volume, is that the total water volume can be subdivided into bound fluid and free fluid fractions, the specific retention and specific yield. The specific retention is an estimate of the volume of water that will remain in the rock following dewatering, and so can be used to represent how much water will be present in the rock mass when it is mined, while the specific yield represents the volume of water that will be removed during dewatering. Following the example above for dry bulk density, it is possible to describe the mass and volume of a rock mass as:

$$Mass = V_{ma} \cdot \rho_{ma} + V_{bound} \cdot \rho_w = \rho_b - V_{free} \cdot \rho_w - V_a \cdot \rho_a = \rho_b - \frac{\phi_{BMR}}{\phi_{BMR_w}} \cdot \rho_w$$

$$Volume = V_{ma} + V_{bound} + V_{free} + V_a = 1$$

In these equations, the total volume of water is subdivided into bound water (V_{bound}, 1) and free water (V_{free}, 1) volumes. In hydrogeological nomenclature, the free water volume is known as the specific yield (S_y, 1). Combining these equations and assuming that the specific yield represents the volume of water removed during dewatering allows to predict the in-situ bulk density of a rock mass (ρ_{ib}, g/cm^3) following dewatering as:

$$\rho_{ib} = \rho_b - S_y \cdot \rho_w$$

This estimate can be used to predict tonnage of moist rock to be transported and processed for mine planning.

The key to the successful application of this method is that borehole magnetic resonance supplies a lithology-independent measure of water content in a rock. This contrasts with other borehole geophysical measurements, which respond to either the properties of both the rock matrix and pore fluids, such as sonic measurements, or respond to both the volume and arrangement of pore fluids, such as resistivity measurements. Similar methods have been proposed for use with neutron porosity measurements, which are also sensitive to the amount of hydrogen present in a rock, however except in very simple lithologies the neutron porosity cannot be taken directly as a measure of porosity or water content. Neutron porosity is sensitive to all hydrogen, so any hydrogen contained in the rock framework will contribute to the neutron porosity measurement. A secondary influence on neutron porosity response is formation density. The elastic scattering process that slows neutrons is most effective for collisions with hydrogen nuclei, but all nuclei contribute, and there is a general reduction in elastic scattering efficiency with atomic number of the nucleus involved. Therefore, variations in average atomic number of a formation, which relate to density, also result in variations in the amount of neutron slowing, which is reflected in the measured porosity. Finally, thermal neutron absorbers such as gadolinium, boron, and chlorine can capture thermal neutrons before they can be detected, removing them from the thermal neutron population and therefore influencing the measured porosity. These effects, which are generally related to lithology, can cause neutron porosity to be significantly different from the actual water content, limiting its use for this sort of analysis.

CONCLUSIONS

Borehole magnetic resonance provides lithology-independent measurements of water content in rocks. This data, combined with bulk (gamma-gamma) density measurements, can be used to derive several densities used in mineral resource estimation and mine planning. The combination of measurements can be used to estimate dry bulk density for mineral resource estimation under all conditions. These measurements can also be used to derive matrix density in fully water-saturated rocks. Finally, taking advantage of the sensitivity of borehole magnetic resonance measurements to both pore volume and pore geometry, the fractions of bound and free water in a rock can be determined, and these can be used with bulk (gamma-gamma) density measurements to predict the density of a partially saturated rock mass after dewatering for mine planning.

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