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Effective stress, porosity, velocity and abnormal pore pressure prediction accounting for compaction disequilibrium and unloading

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ABSTRACT

Abnormal pore pressures, mostly overpressures, exist in many sedimentary formations. The overpressures deteriorate drilling safety, causing borehole influx, kicks, and even blowout, if the pressures are not accurately predicted prior to drilling. Highly anomalous overpressures may also induce instability and reactivation of faults, causing fault weakness. Formation overpressures are primarily generated by compaction disequilibrium, which is often recognized by higher than expected porosities at a given depth and the porosities deviated from the normal porosity trend. Based on this mechanism, the paper proposes a new generalized theoretical model for porosity–depth relationship for both normally compacted and abnormally compacted formations, i.e., $\phi = \phi_0 e^{-cZ(\sigma_e/\sigma_n)}$. This model leads to a new method for calculating effective stress and pore pressure in subsurface formations using porosity and compressional velocity. A new relationship of the transit time and depth has also been derived which extends the existing model (Chapman's model). It demonstrates that the sonic/seismic travel time and effective stress have an exponential relationship (i.e., $\Delta t = \Delta t_m + (\Delta t_{ml} - \Delta t_m)e^{-cZ(\sigma_e/\sigma_n)}$).

Stress unloading caused by formation uplift has a different path compared to compaction/loading curve of the stress and velocity, thus a different compaction constant. This causes a smaller effective stress and lower porosity than those in the loading case; i.e., unloading causes pore pressure increase. Effective stress and pore pressure calculations accounting for unloading are also proposed. Field data in several petroleum basins are analyzed and verify the theoretical relationship between effective stress and sonic transit time. Lab experimental data in sonic velocity and effective stress in both loading and unloading cases also verify the proposed effective stress and velocity relationship. Case study in an oil field is presented to examine the proposed model for pore pressure analysis in subsalt formations.

1. Introduction

1.1. Under-compaction and abnormal pore pressure

Pore pressures in subsurface formations vary from hydrostatic pressures (normal pore pressures) to severe overpressures (more than double of the hydrostatic pressures). Overpressures exist in many geologic basins in the world. If this abnormal overpressure is not accurately predicted before drilling and while drilling, it can greatly increase drilling risks and incidents. For examples, in deepwater of the Gulf of Mexico, incidents associated with pore pressure and wellbore instability accounted for 5.6% of drilling time in non-subsalt wells, and 12.6% of drilling time in the subsalt wells (York et al., 2009). The abnormally high pore pressures also caused serious drilling incidents, such as the fluid kicks and well blowouts (Skalle and Podio, 1998; Holand and Skalle, 2001). Therefore, pore pressure prediction is critically important for drilling planning and operations in oil and gas industry. Abnormally high pressures also induced geologic hazards and disasters, such as weakness in faults (e.g., Bird, 1995; Tobin and Saffer, 2009) and mud volcanoes (Davies et al., 2007; Tingay et al., 2009).

Overpressures can be generated by many mechanisms, such as compaction disequilibrium (under-compaction), hydrocarbon generation and gas cracking, aquathermal expansion, tectonic compression (lateral stresses), mineral transformations (e.g., smectite–illite transition), and hydrocarbon buoyancy (Swarbrick and Osborne, 1998). The major reason of abnormal pore pressure is caused by abnormal formation compaction (compaction disequilibrium). When sediments compact normally, formation porosity is reduced at the same time as pore fluid is expelled. During burial, increasing overburden stress is the prime cause of fluid expulsion. If the sedimentation rate is slow, normal

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compaction occurs, i.e. equilibrium between increasing overburden and ability to expel fluids is maintained (Mouchet and Mitchell, 1989). This normal compaction generates hydrostatic pore pressure in the formation. When the sediments subside rapidly, or the formation has extremely low permeability, fluids in the sediments can only be partially expelled, and the remained fluid must support all or part of the weight of overburden sediments. This causes abnormally high pore pressure. In this case the porosity decreases less rapidly than it should be with depth, and formations are undercompacted or in compaction disequilibrium. The compaction disequilibrium is often recognized by higher than expected porosities at a given depth and the porosities deviated from the normal porosity trend. Therefore, pore pressure can be calculated from the formation porosities.

1.2. Hydrostatic pore pressure

Normal pore pressure is the hydrostatic pressure caused by the column of pore fluid from the surface to the interested depth. For formations with normal fluid pressure, the pore pressure follows the hydrostatic pressure gradient. The magnitude of the pressure is proportional to the depth below the surface and to the density of the fluid in the pores. That is, the pressure is the same at the same depth within the fluid with a uniform density if the fluid is static. Thus, the hydrostatic pressure can be calculated using the following equation:

$$p_n = \rho_f g h \tag{1}$$

where p_n is the hydrostatic pressure; g is the acceleration due to gravity; ρ_f is the fluid density; and h is the vertical height of the fluid column, as shown in Figure 1.

The equation (Eq. (1)) indicates that the hydrostatic pore pressure depends highly on fluid/water density in the formation. While the density of water is a function of water salinity, temperature, and content of dissolved gases (Chillingar et al., 2002); therefore, there is a general variation in the hydrostatic pressure gradient ($\rho_f g$) at different locations due to different water densities. For instance, the average hydrostatic pressure gradient is usually taken as 0.465 psi/ft (1.074 kg/cm^3) in the Gulf of Mexico, and this corresponds to water with a salinity of 80,000 parts per million (ppm) of sodium chloride at 77 °F (25 °C) (Dickinson, 1953).

1.3. Relationship of effective stress, overburden stress, and pore pressure

Terzaghi's or Biot's effective stress law (Terzaghi et al., 1996; Biot, 1941) is the fundamental theory for pore pressure prediction. The effective stress and pore pressure in vertical direction in one-dimensional condition can be expressed as following (Biot, 1941):

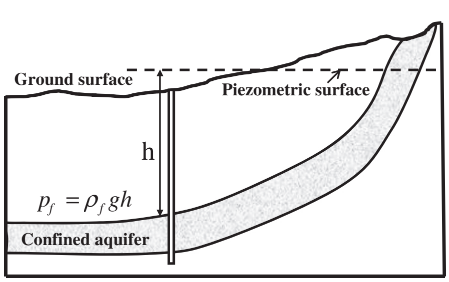

Figure 1. Schematic cross-section showing the hydrostatic pressure caused by water column in a subsurface formation (aquifer).

$$\sigma_e = \sigma_V - \alpha p \tag{2}$$

where p is the pore pressure, σ_V is the overburden or vertical stress, σ_e is the vertical effective stress; α is the Biot's effective stress coefficient.

In normal pressure case, from the above equation the normal effective stress and normal pore pressure have the following relationship:

$$\sigma_n = \sigma_V - \alpha p_n \tag{2a}$$

where σ_n is the normal vertical effective stress; p_n is the normal or hydrostatic pressure.

The effective stress can be obtained by correlating to petrophysical and geophysical data of formations (e.g., resistivity logs, seismic and sonic travel time/velocity). When effective stress and overburden stress are known, the pore pressure can be calculated from Eq. (2).

It is commonly assumed that the in-situ stress includes three mutually orthogonal principal stresses; i.e., vertical, maximum horizontal and minimum horizontal stresses (σ_V, σ_H, σ_h). However, it is further assumed that the formation compaction is mainly caused by the vertical/overburden stress and formation under-compaction is primarily related to the vertical stress (e.g., Chapman, 1983; Osborne and Swarbrick, 1997). Therefore, the pore pressure caused by compaction and under-compaction can be calculated from Eq. (2) when one knows vertical and effective stresses.

Vertical stress is generated by the weight of the overlying formations; hence, it can be obtained by integrating bulk density logs. Therefore, vertical stress can be calculated by the following equation:

$$\sigma_V = \rho_w g z_w + g \int_{z_w}^{z} \rho_b(z) \mathrm{d}z \tag{3}$$

where $\rho_b(z)$ is the formation bulk density as a function of depth; ρ_w is the density of sea water for offshore drilling; z is the depth from the sea level; z_w is the water depth, for onshore drilling $z_w = 0$.

The bulk density can be obtained from well logging. However, in most cases the shallow density log data are not available. Empirical equations can be used to estimate the shallow density. Analyzing the observed depth–density curve in density measurements of shales in northern Oklahoma, Athy (1930) proposed the following equation to interpolate shallow formation bulk density:

$$\rho_z = \rho_0 + A_m\left(1 - e^{-bZ}\right) \tag{4}$$

where ρ_z is the density at the depth of Z, in g/cm^3; ρ_0 is the formation density of the surface; A is the maximum density increase possible ($A_m = \rho_m - \rho_0$ and $A_m = 1.3$ in Athy, 1930); ρ_m is the matrix density or the grain density of the rock; b is the fitting constant. When the bulk density data (ρ_z) are available at certain depths, by fitting the density curve to Eq. (4), the shallow density (ρ_0) can be obtained from Eq. (4).

Another method to calculate shallow formation density is Miller's near surface or mudline density correlation, which can be expressed as follows (Zhang et al., 2008):

$$\rho_s = \rho_m(1 - \phi_s) + \rho_w \phi_s \tag{5}$$

where ρ_m is the average density of the sediment grains (typically 2.68 g/cm^3 for shales); ρ_w is the density of the pore water (typically