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Modified effective medium model for gas hydrate bearing, clay-dominated sediments in the Krishna–Godavari Basin

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ABSTRACT

During NGHP-Expedition-01, well logs were obtained for gas hydrate exploration in Krishna–Godavari (KG) offshore basin. These logs coupled with a suitable rock physics model can be used to understand the interaction between the sediment grains of unconsolidated marine sediments as well as with hydrate. In this paper, we study the friction-dependent effective medium model (EMM) to understand these grain interactions. The compressional (*P*) and shear (*S*) wave velocities of fluid saturated sediments are estimated using different friction parameters at Site NGHP-01-03, which represent the background fluid-saturated marine sediment, and are compared with the observed velocities derived from sonic logs. Our analysis shows that the shear velocity is overestimated for the Hertz–Mindlin contact theory [no-slip across the grain contact], but can be accurately estimated for the Walton's smooth contact model [zero friction across the grain contact]. It suggests that the background shear wave velocity need to be modeled without friction at the grain contact for unconsolidated marine sediments. Further, the friction-dependent EMM theory is tested at Site NGHP-01-07 which represents the load-bearing gas hydrate deposits in KG basin. The comparison between the gas hydrate saturations estimated from sonic and resistivity logs shows that saturations estimated from P-wave velocity match well with those estimated from resistivity and chloride anomaly and is largely independent of the frictional parameter. However, gas hydrate saturations estimated from shear wave velocity is overestimated in the absence of friction but agrees with the other estimates if an arbitrary small friction is included in the EMM.

We further extended the friction-dependent EMM for multi-grain contact (clay + quartz + hydrate) in which the effective modulus of sediment matrix is estimated by accounting for all possible contact combinations among the grains like quartz–quartz (QQ), clay–clay (CC), clay–quartz (QC), quartz–hydrate (QH), clay–hydrate (CH), and hydrate–hydrate (HH). The gas hydrate saturations estimated from shear velocity assuming the same non-zero friction term are underestimated as compared to those estimated from P-wave velocity. Interestingly, the saturations estimated assuming zero-friction from both P- and S-wave velocities are comparable to each other and show a good match with those estimated from resistivity logs and chloride anomalies. The proposed EMM with zero friction and mixed grain contact is able to predict the velocities of fluid-saturated sediments as well as gas hydrate bearing sediments in KG offshore basin.

1. Introduction

Gas hydrate is a naturally occurring, crystallized solid composed of water and hydrocarbon gas (mainly methane) molecules and is stable within a zone of high pressure and low temperature in marine sediments known as the gas hydrate stability zone (GHSZ) (Sloan, 1998). The presence of gas hydrate is inferred from the analysis of seismic and logging data. In the seismic data, the presence of gas hydrate is manifested in the form of anomalous reflector known as bottom simulating reflector (BSR) which represents the interface between the overlying gas hydrate bearing sediments and underlying free gas bearing sediments (Hyndman and Spence, 1992; Singh et al., 1993). In well-log data, its presence is inferred from the increase in electrical resistivity and elastic velocities as compared to that of fluid saturated sediments.

In situ gas hydrate saturations can be estimated from the analysis of logging while drilling (LWD), wireline logs and pressure cores. In order to quantify gas hydrate, a relationship between the

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physical property and gas hydrate/free gas saturation is required. For example, Gas hydrate saturation can be estimated from resistivity data using Archie's equation (Archie, 1942). Likewise, various velocity models based on either empirical relationships or first principles are required for estimating saturations from sonic logs. Depending on the distribution of gas hydrate within the sediments, several rock physics models like the cementation theory (Ecker et al., 1998), effective medium model (EMM; Helgerud et al., 1999), effective medium theory using self-consistent approximation (SCA) and differential effective medium (DEM) (Jakobsen et al., 2000), modified Biot–Gassmann theory (Lee, 2002), three-phase Biot type equation (TPBE; Carcione and Tinivella, 2000; Guerin and Goldberg, 2005; Lee and Waite, 2008) are proposed. A general comparison among these models (Chand et al., 2004) suggests that different rock physics models exhibit similar P- and S-wave velocities for hydrate free sediments, but show marked difference in the velocities of gas hydrate bearing sediments.

Drilling/coring activities during National Gas Hydrate Program Expedition-01 (NGHP-01) has established the presence of gas hydrate in Krishna–Godavari (KG), Mahanadi and the Andaman basins (Collett et al., 2008, 2014; Kumar et al., 2014). In some cases, massive hydrate is visually observed in the sediment cores from KG basin. In most cases, pressure cores were deployed to confirm the presence of gas hydrate. Sedimentological data reveals that sediments in KG and Mahanadi basins are clay dominated with 85–95% clay and 5–15% silt (Collett et al., 2008).

Several rock physics theories have been formulated for gas hydrate bearing sediments in KG offshore basin. The pressure core X-ray images and resistivity at bit (RAB) images from Site NGHP-01-10, KG basin, show fracture-filled gas hydrate in clay dominated sediments (Collett et al., 2008). Based on this observation, Lee and Collett (2009) proposed an anisotropic rock physics model in which the effective properties of the medium are obtained using Backus average theory (Backus, 1962) for different gas hydrate saturations. The study of amplitude variation of BSR with incidence angle in the vicinity of site NGHP-01-10 also suggests that the medium is anisotropic and realistic gas hydrate saturation as well as fracture azimuth can be estimated assuming the anisotropic rock physics model (Sriram et al., 2013). In both of these studies, the TPBE (Lee and Waite, 2008) has been used to model the P- and S-wave velocities of the background clay dominated sediments. The TPBE model depends on a consolidation parameter (Pride et al., 2004) which is a function of pressure/depth and is obtained empirically so that the estimated background P-wave velocity is close to the observed velocity. Such empirical relationship is good for modeling velocities, but it does not give any insight into the physical interaction between the sediments and the gas hydrate. Therefore, we attempt to model the P- and S-wave velocities of clay dominated hydrate bearing sediments using the first principle based effective medium model (EMM) (Dvorkin et al., 1999; Helgerud et al., 1999). We first model the velocities from Site NGHP-01-03 which represents the baseline clay dominated sediment in KG offshore basin, and later model the velocities from Site NGHP-01-07 which represents gas hydrate bearing sediments. We deliberately choose Site NGHP-01-07 as it shows low fracture density and the gas hydrate may be represented by either pore-filling or load-bearing form of gas hydrate and not fracture-filled gas hydrate. The EMM is modified by incorporating inter-particle contact friction parameters (Duffaut et al., 2010; Bachrach and Avseth, 2008) and grain contact model (Hossain et al., 2011) so that the background velocities can be accurately estimated, and the gas hydrate saturations estimated from the sonic log are similar to those estimated from the resistivity log and core derived chloride profile.

2. Development in effective medium model (EMM) technique

The effective medium model (EMM) is based on the first principle physics (Dvorkin et al., 1999) where the effective elastic properties of the identical sphere packs are estimated using the Hertz–Mindlin contact theory (Mindlin, 1949). EMM is used to approximate the behavior of the granular media with many contacts using the average of two-grain contacts. Such contact theory accurately approximates the bulk modulus of sediment matrix, but fails to model the shear modulus (Bachrach and Avseth, 2008; Duffaut et al., 2010). Several experimental studies have reported significant difference between the shear modulus estimated from Hertz–Mindlin contact theory and the laboratory measured shear modulus (Winkler, 1983; Goddard, 1990; Zimmer et al., 2007). The numerical granular dynamics model (Makse et al., 1999) suggests that the Hertz–Mindlin contact theory fails to predict the shear modulus because the grains tend to relax from the macroscopic deformation or rotate leading to the breakdown of uniform strain assumption. Accurate shear wave estimation is important for several geophysical studies such as reservoir modeling using amplitude variation with offset, vertical seismic profiling (VSP), and identification of the fluid type, lithology and other mechanical properties. Error in estimation of the S-wave velocity may lead to an error in Poisson's ratio, impedance, V_P/V_S ratio and fluid factor.

The problem of incorrect S-wave velocity was addressed initially by Bachrach and Avseth (2008) by considering non-uniform contact and heterogeneous stress fields in effective medium. A binary scheme was introduced where the grain contact can be either smooth with zero tangential stiffness or no-slip with tangential stiffness estimated from Hertz–Mindlin contact theory. The effective elastic modulus is then estimated from the combination of smooth and no-slip contacts using a parameter f_t which represents the fraction of no-slip contact. Such binary model for grain contact gives more reliable estimate of shear modulus (Bachrach and Avseth, 2008). Duffaut et al. (2010) extended the EMM by introducing partial slip with nonzero contact friction and a free parameter, Mindlin friction term $f(\mu)$, which represents the ratio between the radii of the non-slip contact area and of the full contact area. In this frictional dependent model, the effective shear modulus of the identical sphere pack is derived by combining the tangential contact stiffness estimated from Mindlin's theory (Mindlin, 1949) with the effective modulus expression derived by Digby (1981). The free parameters, Mindlin's friction term (Duffaut et al., 2010) and the fraction of no-slip contact (Bachrach and Avseth, 2008), of the modified effective medium theories are estimated from the laboratory studies of dry bulk and shear moduli of core samples. The friction parameter $f(\mu)$ can also be estimated from the dry bulk and shear moduli (Duffaut et al., 2010; equation (B1)) calculated from sonic log using Gassmann's equation (Gassmann, 1951). These models show similar estimates of bulk and shear moduli and match well with the stress–velocity data of glass beds and loose sand (Zimmer, 2003; Zimmer et al., 2007).

3. Log data and methodology

Several well logs were acquired in the clay dominated marine sediments in Krishna–Godavari basin for gas hydrate exploration (Collett et al., 2008). In this study, we have considered the Site NGHP-01-03 located in KG Basin (15°53.891′ N, 81° 53.9678′ E) at water depth of ~1076 m (Fig. 1). At this site, negligible gas hydrate saturation has been reported from the analysis of resistivity logs as well as from the pressure core data (Collett et al., 2008); therefore, the site represents the properties of fluid-saturated marine sediments in KG offshore basin. The logging while drilling (LWD) data was recorded to a depth of 300 mbsf (meters below seafloor) and