Abstract

Natural gas-hydrates are non-stoichiometric ice like crystalline solids composed of hydrogen bonded water cages entrapping gas (mainly methane) molecules as “guest”. Gas-hydrates is stable at high pressure and low temperature present in the shallow sediments of most of the continental margins and deep inland seas and permafrost regions of the world. Huge amount of methane is believed to be trapped in nature in the hydrate-bearing sediments underlying free gas-bearing sediments. This large reservoir of methane may be a viable source of future energy resource. Gas-hydrates play an important role in global climate change, as dissociation of gas-hydrates by some phenomena releases methane (green house gas) into atmosphere. The formation or dissociation of Gas-hydrates also has a strong effect on sub-sea slope stability. Therefore, it is essential to evaluate gas-hydrates for the resource potential and hazard assessment. The energy potential of gas-hydrates is more than double the energy contained in the fossil fuels. If we produce only 15% gas from gas-hydrates, it can meet the global energy demand for the next 200 years at the current rate of consumption. A remote sensing technique, which can accurately assess the amount and distribution of gas-hydrates in natural deposits, is necessary for the assessment of gas-hydrates.

Seismic reflection profiling is the best technique for remotely probing sediments several hundred meters below the surface underlain by another few hundred meters of water columns. Presence of gas-hydrates increases both the P- and S-wave seismic velocities of the sediments, whereas underlying free gas reduces the P-wave velocity appreciably without affecting the S-wave velocity. Interpreting velocity ‘build-up’ requires a relation between the hydrate fraction in the sediments and the elastic properties of the hydrate-sediment composite. Unfortunately, very little is known about the role of gas-hydrates in modifying the elastic properties of the hydrate-bearing sediment. The growth habit of Gas-hydrates in sediment are categorized into six basic types: gas-hydrates (1) grow at the grain contact, (2) coat the grains, (3) develop in the interior of the porous frame and support the overburden together with the grains, (4) is a part of the pore fluid, (5) is uniformly distributed in the rock matrix like the ice layer in permafrost, and (6) form as nodules, fracture-filling veins. Models 1-5 are pore-filling morphologies, which consider gas-hydrates as homogeneously and isotropically distributed in

sediments. Drilling in gas-hydrates provinces shows model 6, grain-displacing morphology of gas-hydrates, and is common in the shallow shaly sediments.

A range of rock physics models have been developed to interpret velocities in terms of gas-hydrates and free-gas saturation. The advantage of models based on empirical relations is that it is formulated from real data and simple to apply. However, they may not be applied in areas having rock properties different from where they were formulated. The rock physics models based on simple effective medium theory assume homogeneous and isotropic sediments constituting grains of spherical shape. In reality, most of the sedimentary basins are made of shale (rich in clay minerals) that exhibit inherent anisotropy due to orientation of clay platelets and the microstructure of sediment becomes complex. Therefore, the homogeneous and isotropic assumption will introduce error in estimating the elastic properties of clay-rich hydrates-bearing sediments. After reviewing several different methods, an effective medium theory (EMT), which is a combination of self-consistent approximation (SCA) and differential effective medium (DEM) theory coupled with smoothing approximation of crystalline aggregate, is selected for calculating the elastic properties with a view to assessing gas-hydrates from measured velocities.

The effective medium is constructed by embedding inclusions of one material within another material. In clastic sediments grains and pore-fluids are fully connected (bi-connected medium) at all realistic porosities. But SCA and DEM individually can not model such medium which is bi-connected at all porosities. SCA produces bi-connected medium within 40-60% porosity and not valid above 60% porosity. DEM models micro-structure of a medium but it depends absolutely on the starting medium. If starting medium is biconnected which can be modelled by SCA within 40-60% porosity, the DEM calculates the effective elastic properties preserving the bi-connectivity of the medium at all porosities. In this combined effective medium theory, two end member distributions of gas-hydrates are considered: (1) non-load bearing gas-hydrates – in which gas-hydrates are part of pore fluid and (2) load-bearing gas-hydrates – where gas-hydrates cement the grains and form a continuous matrix. Roles of water and gas-hydrates are interchanged in these two models of gas-hydrates distribution.

In the EMT, clay is taken as the connected and silt minerals are taken as the isolated inclusion phases. Clay-rich sediment has inherent anisotropy due to the alignment of ellipsoidal clay-platelets. In reality, groups of clay-platelets may consist of fully aligned particles, but the orientation of these aggregates may vary depending on the depositional and stress history of the sediments. The orientation of such groups of clay platelets (domains) varies from completely aligned (transversely isotropic) to completely random (isotropic). The average elastic properties of these partially aligned domains are computed using the method of smoothing as proposed by Jakobsen et al. (2000).

Resistivity at-bit (RAB) images and pressure cores reveal that gas-hydrates morphology in the clay-rich sediment varies from complex vein structures (grain-displacing) to invisible pore-filling material. The sizes of grain-displacing gas-hydrates vary from thin veins of a few microns in width to nodules of tens of centimetres or even meters in diameter. There is no quantitative treatment of grain-displacing morphology (vein structure) of gas-hydrates in literature. But saturation of gas-hydrates, estimated on assumption of pore-filling morphology, certainly misleads for fractured fine grained sediments. First time, we apply the differential effective medium theory to incorporate the grain-displacing (veins or fractures) morphology and estimate gas-hydrates saturation from velocities observed in the fractured Gas-hydrates reservoir.

We have applied the EMT to estimate gas-hydrates and/or free-gas in four different geological/tectonic environments: (i) gas-hydrates and free-gas existing in the clay-rich Blake Ridge area (East coast of the U. S., Atlantic continental margin) and the Cascadia margin (off Vancouver Island, Pacific Ocean), (ii) massive gas-hydrates occurring in fractured shale (Site 10 of the Krishna-Godavari (KG) basin in the Bay of Bengal), (iii) gas-hydrates existing in sand layers within the clay-rich sedimentary column (Site 15 of the KG basin in the Bay of Bengal) and (iv) gas-hydrates and free-gas existing in turbidite sand/silt rich sediment in the Makran accretionary prism (Arabian Sea).

Gas-hydrates and free-gas are evaluated from the vertical seismic profile (VSP) velocities at Sites 994, 995, and 997 of the Blake Ridge and seismic velocity-depth function at ODP Site 889/890 (L89-08) of the Cascadia margin. The distribution pattern of clay platelets used by Jakobsen et al. (2000) is considered for the orientation distribution pattern in both regions. The average saturations of gas-hydrates, estimated from the VSP velocities within the Gas-hydrates stability zone, are 10-11 %, 10-13 % and 11-14 % of pore space at Sites 994, 995 and 997 respectively at the Blake Ridge, whereas, the average concentrations of free gas are ~2 %, ~1 % and ~2-2.6 % of total porosity respectively. In Cascadia margin, the average saturations of gas-hydrates and free-gas are estimated from seismic velocity as ~17 % and ~0.45 % of pore space respectively.

For Site 10 in the KG Basin, we consider three types of gas-hydrates morphology: (i) grain-displacing, (ii) grain-displacing and pore-filling and (iii) pore filling. Saturations of gas-hydrates, estimated from the sonic log for three cases, are 13.5-33, 22.5-59 and 15-48 % of total porosity respectively within the depth of 60-140 m below sea floor. Here, we consider the range of aspect ratios (flat to sphere) for fractures and completely aligned to random clay platelets to evaluate possible range of hydrates saturation. This may open up new avenue for future research. At Site 15 in the clay-rich KG Basin, we use the EMT first to determine the orientation distribution function (ODF) from other information (like sonic velocity, density log etc available in a nearby well) as there is no published information of the ODF of the clay platelets. The ODF, which depends on two coefficients, shows W_{400}=0.0508 and W_{200}=0.0248. The maximum saturation of gas-hydrates at this site estimated from the sonic log is ~50% at around 80 mbsf, whereas the saturation is estimated as 5-10% in other sand layers at different depths.

We show that in areas where porosity and mineralogy are not explicitly known, the EMT still can be used if a reference (background) velocity profile in near-by areas with no hydrates can be matched with a reasonable porosity and volume fractions of minerals. In case of turbidite sand/silt rich sediment in the Makran accretionary prism, the clay platelets can be assumed to be completely disordered that exhibits isotropic behaviour of sediments. The porosity-depth function is calculated using the Athy’s law. Like, Cascadia margin, here also we determine the mineralogical constituents using the EMT from the background velocity-depth trend. The maximum gas-hydrates and free-gas saturation across the BSR are estimated as 22 % and 2.4 % of pore space respectively.

The gas-hydrates and free-gas saturation estimated using the EMT are compared with other standard geophysical and geochemical techniques such as the pressure core analysis, Archies’ Law using resistivity log, NMR (Nuclear Magnetic Resonance) log, pore-water chlorinity available in the KG basin. An important drawback in estimation of gas-hydrates from the resistivity log using Archie’s law is the uncertainty in the Archie’s relation parameters (*a*, *m*, and *n*), particularly for the fine grained sediment. A small difference in these parameters can lead to a large difference in saturation estimation of gas-hydrates. Moreover, gas-hydrates act as pore-water freshening and therefore the measured resistivity is a combined effect of gas-hydrates and pore-water freshening, which produces higher resistivity and thus overestimate the saturation of gas-hydrates. Assessment of gas-hydrates from pore-water freshening depends on the insitu chlorinity values, which is calculated from downhole resistivity log. Therefore, similar uncertainties also arise for quantification of gas-hydrates from the chlorinity values. The porosity deduced from the NMR log is the water-saturated porosity, because solid hydrates in the pore spaces can be “seen” by this device as part of the matrix. Therefore, NMR porosity subtracted from the total porosity measured by

the density log can give the hydrates saturation directly. But the NMR tool, used till date, underestimates the porosity measurement, which, in turn, overestimates the hydrates saturation. Samples recovered and analyzed at insitu conditions (e.g. pressure cores) provide the direct and accurate insitu quantification and morphology of gas-hydrates. Though direct and accurate quantification of gas-hydrates is possible from pressure cores, the main drawback is that even in continuous coring programs; core recovery is hindered by several effects like exsolution, dissociation and expansion of gas. Therefore, interpretation of velocity (seismic, sonic or VSP) using a best suitable rock physics model provides the concentration of gas-hydrates and free-gas continuously with depth. We conclude that the combined SCA-DEM theory is the best suitable rock physics model for fractured/unfractured clay-rich sediments. The isotropic SCA-DEM theory (when clay platelets are randomly oriented or all the mineralogical constituents of the sediment are assumed as spherical) is suitable for gas-hydrates existing in sand rich sediment. Though the combined SCA-DEM theory was elaborated for estimation of gas-hydrates having pore-filling morphology in clay-rich sediment, it has been established here that the theory can be applied to estimate gas-hydrates having grain-displacing morphology and free-gas saturation also. The theory also works well for sand-rich sediment, illustrated through a field example in the Makran Accretionary Prism.