Stochastic simulation of resistivity of gas hydrate reservoir in Krishna-Godavari Basin

Soumya Jana*, Maheswar Ojha and Kalachand Sain
CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad-500007
*Presenting author email: soumya.jana89@gmail.com

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Summary
The occurrences of gas hydrates in pore spaces of sediment change the velocity and resistivity of the sediments. Since the well-log data have high frequency, it contains small scale heterogeneities of gas hydrate bearing sediments. Here, we have incorporated these small scale heterogeneities by generating a stochastic 2-D resistivity and density models from well log data in Krishna-Godavari basin. Gas hydrate saturation has been estimated over these simulated 2-D heterogeneous resistivity model using Archie’s equation.

Study Area and Data
Resistivity and density logs were collected during Expedition-01 of Indian National Gas Hydrate Program (NGHP Exp-01) in 2006 (Collett et al., 2008) at a site NGHP-01-10 located at 15°51.8669’ N, 81°50.0749’ E in central part of Krishna Godavari (KG) basin (Fig. 1). Logging While Drilling (LWD) data has been used to simulate stochastic 2D model. Pressure cores data available at this site is used to validate the saturation estimated from resistivity data. Water depth at this site is about 1038 m. The bottom simulating reflector (BSR) is observed at a depth of ~158 meter below seafloor (mbsf) in resistivity log (Fig. 2a).

Methodology
We have used a spectral based approach to simulate 2D field from observed logs (Huang et al., 2009; Jana et al., 2015). A log data contains both long wavelength part (water saturated part) shown by red line in Fig 2a & 2c and short wavelength part (residual heterogeneous part). Long wavelength part is removed from observed log and residual is downscaled to zero mean and unit standard deviation. This downscaled log is used for heterogeneous modelling. There are six steps for generating synthetic heterogeneous stochastic field:

1. Selection of an appropriate autocorrelation function by fitting it to autocorrelation of observed logs.
2. Generating of a desired power spectrum by doing FFT or DFT of autocorrelation function.
4. Computation of a phase spectrum, \( \exp(i\phi) \), \( \phi \) is a random number uniformly distributed on the interval \([0,2\pi]\).
5. Multiplying Amplitude and Phase spectrum to get Fourier spectrum.
6. Inverse FFT or DFT of Fourier spectrum to generate a field.

Figure 1: Location of the study area in KG basin.

Figure 2: (a) Resistivity log with a linear background trend (red line) showing BSR at depth of 158 mbsf. (b) Resistivity over gas hydrate bearing zone between 27 to 158 mbsf. (c) Observed density log with a linear background trend (red line). (d) Density over gas hydrate bearing zone.
We have chosen Von Karman autocorrelation function to simulate random heterogeneous stochastic model which includes fractal dimension (D) of the field by Hurst coefficient (ν) as D = E + 1 − ν. E is Euclidean dimension. Von Karman ACF is given by (Goff and Jordan, 1988)

\[ C(r(X)) = \frac{r^2 K_v(r)}{2^{\nu-1} \Gamma(\nu)} \]  

where, \( r(X) = \sqrt{\frac{x^2}{a_x^2} + \frac{z^2}{a_z^2}} \).

\( a_x \) and \( a_z \) are characteristic scale along x (horizontal) and z (vertical) direction respectively, \( \nu \) is the Hurst coefficient, which measures the smoothness of field and it has value between 0 and 1. \( K_v(r) \) is modified Bessel function of second kind of order \( \nu \). \( \Gamma(\nu) \) is the Gamma function.

The Hurst Coefficient (ν) and Vertical Characteristic Scale (\( a_z \)) is obtained by fitting Von-Karman autocorrelation function to autocorrelation of resistivity and density log. Vertical characteristic scale and Hurst co-efficient are 9.4846 m and 0.775 for resistivity simulation, and 13.0458 m and 0.69 for density simulation. Horizontal Characteristic Scale (\( a_x \)) can be calculated from horizontal logs. Since, we do not have horizontal log, thus, we have simulated a number of fields with different values of horizontal characteristic scale. According to Weiner-Khinchin transform pair Fourier transform of auto-correlation Function gives Power Spectrum Density Function (PSDF). PSDF of Von-Karman distribution for 2-D is given by (Huang et al., 2009) as

\[ S(k) = \frac{4\pi a_x^2 a_z^2}{(1 + k^2 a_x^2 a_z^2)^2} \]  

where, \( |k| = \sqrt{k_x^2 a_x^2 + k_z^2 a_z^2} \).

Now with this PSDF, simulated gaussian field can be generated by following steps mentioned above.

It is noted that density simply follows gaussian distribution as density of gas hydrate is close to water density and almost unchanged in presence of gas hydrate, but resistivity follows bimodal distribution because presence of gas hydrate in sediments increases resistivity of sediment significantly. According to central limit theorem, simulated stochastic field is asssymtotically Gaussian. Thus, density field is simulated directly, but, Gaussian resistivity field is mapped into non-gaussian bimodal field by a non-linear mapping technique. Finally, The mean value of observed log is added to the mapped stochastic field, followed by a multiplication of the standard deviation to get field with desired mean and standard deviation.
Results: Gas Hydrate Saturation

We have estimated amount of gas hydrate over an area of 500m x 131m simulated heterogeneous resistivity and density models (Fig. 5). For estimating hydrate saturation from resistivity, we need to calculate the electrical resistivity of background water-saturated sediments ($R_w$) which is obtained from the Archie’s equation (Archie, 1942) as follows:

\[
F = \frac{R_0}{R_w} = \frac{a}{\phi^m}
\]

(3)

where, $F$ is formation factor, $R_w$ is the resistivity of formation water, $a$ and $m$ are Archie’s parameters, and $\phi$ is the porosity. The value Archie’s parameters, $a=3.2$ and $m=0.5$ are derived from the cross-plot of formation factor (F) with respect to original porosity log ($\phi$) (Lee and Collett, 2009). We calculate porosity from observed density log (Fig. 1c) assuming grain density 2.71 g/cc and $R_w$ using Arp’s formula (Arp, 1953), with a measured salinity of 32.5 parts per thousands, temperature gradient of 45 °C/km, and seafloor temperature of 6.5 °C (Collett et al., 2008). Arp’s formula is written as $R_{w2} = R_{w1}(T_1 + 7)/(T_2 + 7)$, where, $R_{w1}$ and $R_{w2}$ are water resistivity at Fahrenheit temperature at $T_1$ and $T_2$ respectively.

Gas hydrate saturation ($S_h$) from simulated resistivity (R) is estimated by equation given below:

\[
S_h = 1 - \left( \frac{aR_w}{R\phi^n} \right)^{1/n}
\]

(4)

where, $n$ is saturation exponent which is derived empirically. The parameter $n$ has value equal to 2 for unconsolidated sand. For gas hydrate, value of $n$ may varies from 2 to 7 (Kennedy and Herrick, 2004) depending upon anisotropic distribution of hydrate. Here, we are getting a good match between the saturation values obtained from equ. 4 with the direct measurement of saturation from the core samples for $n=6$ (Fig. 6).

Average hydrate saturation is about 33.90 % of pore volume over 2-D saturation model (500m x 131m) shown in the figure below:

![Figure 6: (Left) Measured resistivity (black), formation water resistivity (purple) with water saturated sediment resistivity (red). (Right) Saturation derived from measured resistivity log with $a=3.2$, $m=0.5$, $n=2$ (brown) and $n=6$ (blue), and direct hydrate saturation estimated from the pressure cores at sites NGHP-01-10 (green dots).](image)

![Figure 7: 2-D saturation model for different horizontal characteristic scale.](image)

Discussion and Conclusion

In this work, gas hydrate bearing zone is modelled by generating a 2-D random heterogeneous medium, which includes all stochastic features (rms fluctuations, fractal dimension, characteristic scales) of observed well log data. To check the validity of simulated field, first we have generated stochastic 1-D field of resistivity and density and compared average saturation from both 1-D simulated field and observed logs. We have found that average saturation at log location from both observed and simulated 1-D field are almost same. Estimation of saturation from 2-D simulated stochastic heterogeneous resistivity field containing all small and large scale
heterogeneity are more accurate and reliable because resistivity filed is not affected by anelastic attenuation like scattering, absorption which have effect on velocity.

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