# Reservoir Geomechanics in the Gas Hydrate Bearing Sediments in the Mahanadi Basin

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**Keywords**

Pore pressure, in-situ stress magnitude & orientation, rock mechanical properties, wellbore stability, stress polygon, gas hydrates

## Abstract

Solid gas hydrates presence in the continental margin of India could are the potential energy source that can mitigate India's growing energy demand. Two major expeditions (NGHP-01 & NGHP-02) were carried out to explore the gas hydrates reservoirs in India's offshore basins and as well as to characterize the various parameters for its quantifications. During future extraction of the gas hydrates, it could trigger several problems like seafloor slop failure, subsidence, and methane gas leakage. It may also create wellbore instability and other associated problems. Therefore, the study of geomechanics and its parameters are crucial to reduce the risk of the above-mentioned geo-hazards. Due to changes of pressure/temperature from equilibrium condition, there are changes in the geoemchanical parameters. Moreover, extraction of gas hydrate is a thermal-mechanical and chemical coupling process that could lead to several geomechanical issue during the production. Therefore, the objective of this paper is to compute and estimate all geoemchanical parameters for the NGHP-01 sites in the gas hydrates bearing sediments in the Mahanadi basin using well log and seismic data. First, geomechanical parameters such as pore pressure, minimum and maximum horizontal stresses and their orientation from image log data, and rock mechanical parameters will be discussed from well log data at NGHP-01 sites and then mapped their spatial distributions in the gas hydrates bearing sediments using seismic data.

## Introduction

Gas hydrates are usually solid ice-caged structures that are made by methane gas being trapped within the water molecules at low temperature and high pressure (Collett et al. 2008; Kumar et al. 2014). Gas Hydrates contain immense amount of energy and the guest gas molecule stabilizes structure of gas hydrates. – Almost twice of energy contained in fossil fuels. Gas hydrate fields world over have been initially recognized from the detection of anomalous acoustic reflections on the industry acquired conventional multichannel seismic (MCS) reflection data. This anomalous reflection is popularly known in the geoscientific community as the bottom simulating reflection or BSR.

India has several offshore proven petroliferous basins for gas hydrates deposition. The Krishna-Godavari offshore basin and Mahanadi offshore basin are the best examples in the eastern continental margin of India. At NGHP-01 sites, gas hydrate was found as fracture-filling in impervious clay rich formations (Collett 2008), and no technique has been developed yet to recover gas hydrate from such formations where lack of permeability and unconsolidated formations causes sediment production and low gas flow rate (Moridis et. al 2010). Gas hydrate in permeable coarse-grain sand formations is considered best reserve for gas production as high intrinsic permeability of such formations enable it to transmit pressure and temperature perturbance from production well to achieve dissociation of gas hydrate and give path to the released methane gas to the production well As a result, NGHP-02 was targeted to be conducted in sand rich permeable formations to find highly gas hydrate saturations zones. One of the leading techniques for gas hydrate exploitation is supposed to be the depressurization technique causes an increase in effective stress in the sediments and reduces stiffness and strength that are linked with prior information of current in-situ stress (Uchida et al. 2019). The success of the depressurization for gas hydrate production would depend on the permeability of the sealing formation. It is also noticed that vertical permeability of gas depends on the vertical stress but the horizontal permeability which is four times of vertical permeability, horizontal in-situ stress related with horizontal permeability of the cap rock (Jang et al., 2019).

Fundamentals of geomechanics include rock mechanical properties, the pore pressure and, the study of in-situ stresses in the subsurface and orientation of in-situ stresses of the subsurface (Bell, 1990). A thorough understanding of in situ stress conditions and rock properties, such as compressive strength, elastic moduli and anisotropy are required to optimize the wellbore design.

In this extended abstract, we focused on the gas hydrates bearing sediments in the Mahanadi basin only and did geomechanical investigation using well log and seismic data at NGHP-01 site.

## Study Area & Data Availability

In the Mahanadi offshore basin, TOC (<1.0->1.5%) and low temperature derived from IR images strongly indicate the suitability for gas hydrate exploration. In the Mahanadi basin, the gas hydrate reservoir discovered during NGHP Expedition-01 is typically located in clay/silt-dominated fracture filling sediments of Pleistocene age (Sain and Gupta, 2012). 'Collett et al (2008) reported promising clay-rich gas hydrate prospect from drilling and logging while drilling (LWD) data recorded during NGHP Expedition 0. The high-resolution two-dimensional (2D) multi-channel seismic data (MCS) and conventional well log data allow to accurate mapping of the subsurface of the offshore.

In this study, we have considered one seismic profiling (MH-38A) in the north to south direction, and three well log data namely, NGHP-01-19, NGHP-01-09 and NGHP-01-08 respectively. NGHP-01-19 is passing through the seismic lines MH-10A and MH-38A whereas NGHP-01-09 passing through the seismic line MH-38B. A strong BSR occurs at a depth of ~257 mbsf. The section below the BSR occasionally shows increased amplitudes; this is likely due to the presence of free-gas. Porosity and resistivity curves in Hole NGHP-01-08A (acquired by LWD) generally mirror each other, suggesting that little or no gas hydrate is present. Below a depth of ~220 mbsf, however, Archie-derived gas hydrate saturations suggest that as much as 10% of the pore space could be occupied by gas hydrate above the BSR or by free-gas below the BSR

## Theory

Reservoir geomechanis deals with three basic parameters, which are pore pressure, in-situ stress magnitude & orientation and rock mechanical properties. Stresses in the earth can be defined in terms of magnitude and orientation of three principal stresses: maximum, intermediate and minimum. For the case of a vertical well (as in the present study), the first principal stress is considered to be vertical, corresponding to the weight of the overburden. The second principal or intermediate and third principal stress are called as maximum and minimum horizontal principal compressive which are denoted by $S_H$ and $S_h$ respectively. The formulae of each parameter are described below:

The overburden / vertical stress (Sv) in the sea calculated from bulk density log of a well, which is force per unit area applied by load of rock above the point of measurement below sea floor. The equation is given below:

$$S_v = \rho_s hg + \int_h^Z \rho(z) g dz \qquad (1)$$

Where, z is depth at point of measurement considering from sea floor of individual well, $\rho(z)$ is the bulk density of the rock, and g is the acceleration of gravity (9.8m/sec$^2$). The sea water density $(\rho_s)$ was taken 1.02 g/cc. h is the sea floor depth.

The effective stress is given by the subtraction between vertical stress and the pore pressure (PP) given by Terzaghi (1996) as

$$\sigma_v = S_v - PP \qquad (2)$$

The pore pressure (PP) is estimated using Bowers (1995) method from the velocity given below.

$$V = V_0 + a\sigma_v^b \qquad (3)$$

Where $V$ is the velocity, $V_0$ is the velocity of sediments at the seafloor (normally, $V_0 \approx 5000$ ft/s or 1520 m/s from Zhang, 2011),'a' and 'b' are the Bower's parameters or fitting parameters.

The rock poroelastic model is used to estimate the magnitude of $S_h$ by the following equation (Eaton, 1972),

$$\mathbf{S_h = PP + \frac{\sigma}{(1-\sigma)}(S_V - PP)} \qquad (4)$$

Where, σ is Poisson's ratio (dimensionless) of the rock. The values of Poisson's ratio have been computed using log data (velocity of compressional/ shear wave) at NGHP-01-19 site, and got vary higher values ranging from 0.42 to 0.48.

The magnitude of $S_H$ estimated at the breakout location in the wellbore using hoop stress or circumferential stress is given below (Barton et al., 1988)

$$S_H = \frac{(UCS+2PP+\Delta P)-S_h(1+2\cos 2\theta_b)}{1-2\cos 2\theta_b} \qquad (5)$$

Where, $2\theta_b$ is π minus the width of the breakout, ΔP is the difference between mud pressures (wellbore pressure) to pore pressure (PP). Uniaxial compressive strength (UCS) has been computed for high porosity clay bearing sediments by using the following equation (Horsrud, 2001),

$$UCS = 0.77\left(\frac{304.8}{\Delta t}\right)^{2.93} \qquad (6)$$

Where, Δt is slowness in μs/ft and UCS in MPa

The whole work procedure is summarized in the flowchart given below.

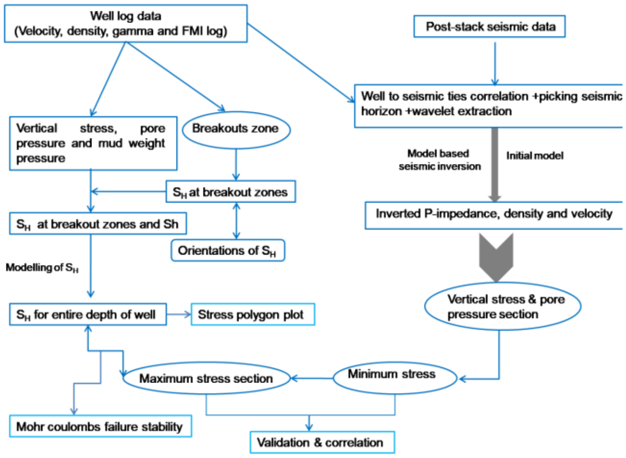


Figure 1: Flow chart to estimate the pore pressure, minimum & maximum stresses and orientation from well data and seismic data

## Results & Discussions

Using the above-mentioned formulae, the results of the pore pressure, vertical stress, magnitude & orientation of minimum and maximum horizontal stress are shown at NGHP-01-09 site and the mapping of the pore pressure and horizontal stresses are discussed below.

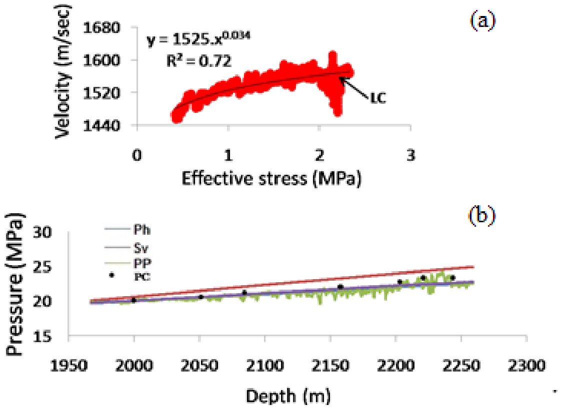


Figure 2: At the NGHP-01-9 sites, (a) is velocity-effective stress cross-plot with loading curve (LC). (b) represents the hydrostatic pressure (Ph), vertical stress (Sv) and pore pressure (PP) using Bower's method.

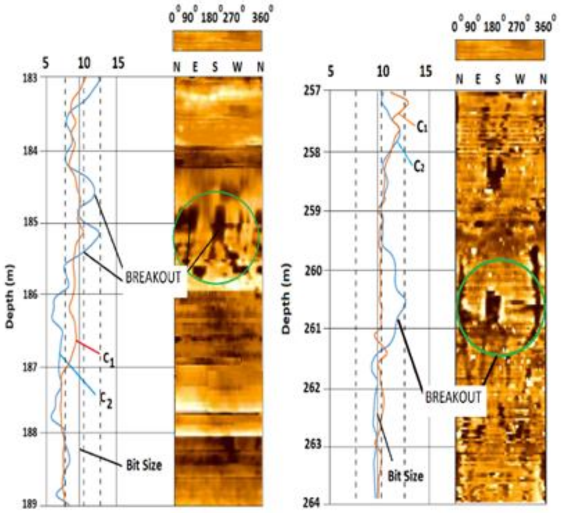


Figure 3: Breakout (BO) are observed from both FMI and caliper log with the depth, bit size, caliper arm and dynamic image log in the wellbore at NGHP-01 site (Shukla et al., 2022).

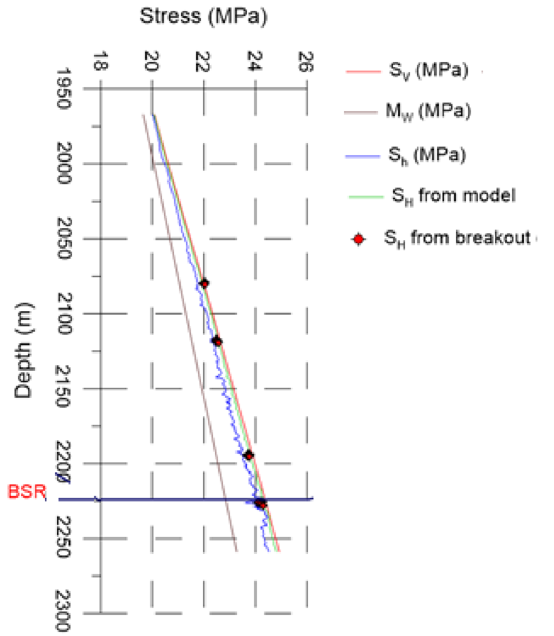
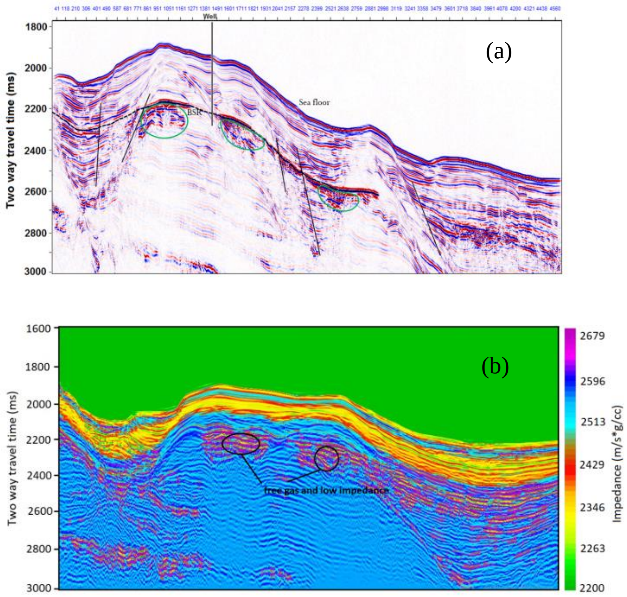


Figure 4: The magnitude of minimum horizontal stress ($S_h$), maximum horizontal stresses ($S_H$) vertical stress (Sv), and mud weight stress ($M_W$) are plotted for the entire well depth at NGHP-01-09 site (Shukla et al., 2022).



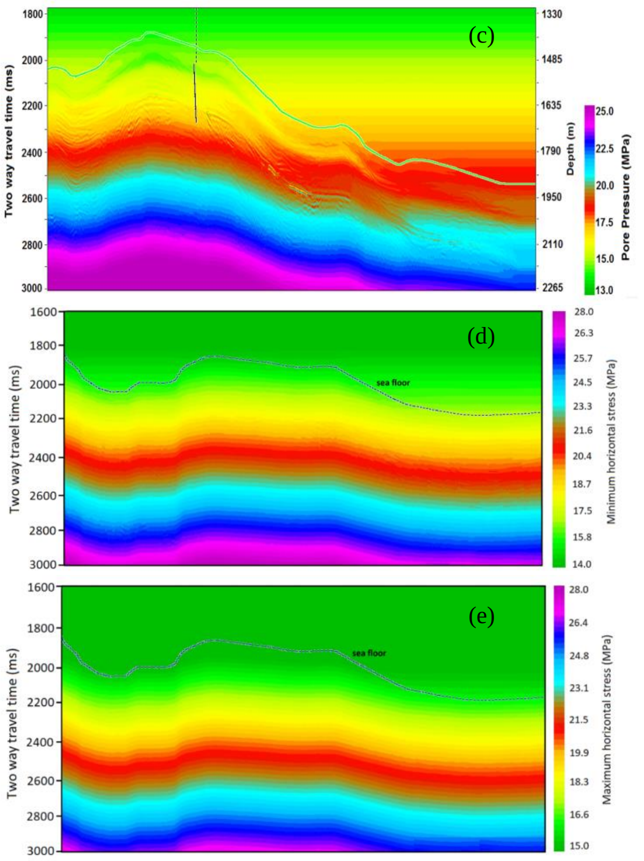


Figure 5: (a) represnt an interpreted seismic profile of line no. MH-38A along SW to NE of the study area, (b) indicates the inverted P-impedance section of the profile obtained using the seismic inversion techniques and then, mapping of pore pressure (c), minimum (d) & maximum horizontal stress (e) in the gas hydrates bearing sediments in the Mahanadi basin (Shukla et al., 2022; Singha et a., 2019).

In the study area, post-stack seismic inversion especially model based inversion has been performed on the seismic data of the profile MH-38A for obtaining the inverted acoustic P-wave impedance, velocity and density (Hampson and Russell, 2006). Acoustic P-wave impedance provides seismic properties of the rock used as a direct hydrocarbon indicator. The signature of free gas has been marked in enhanced reflection below the BSR in the seismic section. The pore pressure gradient is 10.11MPa/km slightly high pressure in free gas sediments below the BSR compared to the pressure above the BSR. The elevated pressure gradient over a large region beneath the GHSZ would push fluids in upper hydrate stability zones. From the sediments above the BSR to the sediments below it, the average gradient of $S_h$ for three wells is changing from 10.41 MPa/km to 10.61MPa/km, whereas for $S_H$, the gradient varies from 10.55 MPa/km to 10.69 MPa/km respectively. The increase of the gradient is due to the phase changes of fluid from solid gas hydrate to free gas in the sediments below the BSR. The analysis of the stress polygon suggests the study area is normal faulting regime implying the stress condition as ($S_V > S_H > S_h$).

Total12 BO's of different lengths were found in selected depth intervals at NGHP-01 sites of the study area classified as D-quality group in world stress map. The maximum length of BO (~3m) in depth interval 184.00-187.00 mbsf is found in the well NGHP-01-09. The orientation of $S_h$ varies from N64.26E to N78.75E, implying that the orientation of $S_H$ ranges from N11.25W to N25.74W in the sediments of Pleistocene age of the study area. The elastic parameters are seen higher in the gas hydrate bearing regions where the lower Poisson's ratio value observed in the free gas bearing zones.

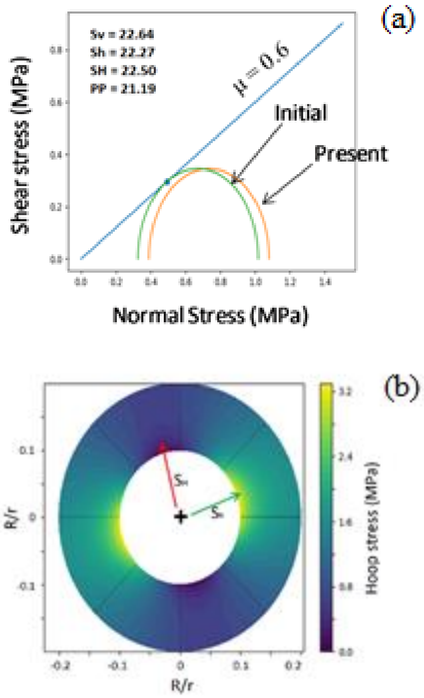


Figure 6: at NGHP-01-09, (a) depicted Mohr circle plot, in present and failure envelope line indicated by green, and (b) Hoop or circumferential stresses distributions around the wellbore wall for BO depth intervals.

For the wellbore stability modeling, The Mohr circle was drawn for depth interval 184-187mbsf at NGHP-01-09 by considering the value $S_v$, $S_h$, $S_H$ and PP given in the figure 6(a) assuming the coefficient of friction ($\mu$) ~ 0.6. These red circle represent the under stable condition or no failures occurred for the depth interval. The distribution of hoop stresses around the borehole was done and shown the effect of hoop stress that reduces with radial axis. The maximum hoop stress happens along the orientation of $S_h$ as marked by the green line.

## Conclusions

This work shows a comprehensive approach for estimating various valuable geomechanical parameters from well log data and 2D multi-channel seismic at site NGHP-01 in the gas hydrate bearing. The pore pressure in the gas hydrate shows normal pressure whereas it increases little high below BSR, indicating free presence of free gas. The maximum stress was computed from the breakout evidence in the wellbore at the sites and normal faulting regime has been established in the study area. Higher elastic values were found in the gas hydrates while Poisson's ratio is little decreasing below the BSR. The wellbore stability modelling shows stable condition. These parameters will be required for creating subsurface modeling of the gas hydrates reservoirs for future production.

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## Acknowledgments

The author would like to thank to the Director, NGRI for sharing the required data set (NGHP-01sites) in the Mahanadi basin with help of Dr Kalachand Sain. The author also thanks to Dr. Pradeep Kumar Shukla for his reserch contributaions and Prof Mrinal Sen for his valuable suggestions. Most of the results, figures and discussions are published in other international journals. The Author also ackowledges the SERB for granting a project under Core Research Grant (FILENO.CRG/2022/003514) for carrying advance reserach in the Gas hydrates reservoirs.