Impulse Response of Seafloor Hydrocarbon Reservoir Model

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Abstract — The step response and impulse response to horizontal electric dipole (HED) source in three typical models such as uniform earth half space, marine double half space and four-layer reservoir-bearing seafloor models were computed, through the use of Gaver-Stehfest inverse Laplace transforms and numerical integration Hankel transforms. And concept of transient impulse time was proposed. It was confirmed that the transient impulse time of the conductive medium to HED can directly indicate the conductivity of the earth. Inline dipole-dipole transient EM sounds with geometry, and it is suitable for surveying with multi offsets. For the high resolution to thin resistive subsurface formations, this method can be applied for hydrocarbons explorations on land, also in marine.

1. INTRODUCTION
Although marine or land 3-D seismic has highest resolution for identifying the possible structure of hydrocarbon reservoir, it cannot make sure whether the structure is filled with conductive water or economic resistive hydrocarbon. Using electromagnetic (EM) method to explore the hydrocarbon reservoir has the good preconditions of physical property, because the electrical resistivity of the subsurface formations is known strongly related to the pore fluids and saturation. The electrical resistivity variation can be detected when the fluids contained in the reservoirs changed from water to hydrocarbon. The method of marine controlled source electromagnetic (mCSEM) has a high ability to indicate the resistive hydrocarbon reservoir [2–4, 1]. At present there are several methods have been developed maturely for hydrocarbon exploration such as seabed logging (SBL) and multi-channel transient electromagnetic (MTEM). The former works in frequency domain with the latter in time domain [3, 4] (Hobbs and Wright, et al., 2005).

Studies in many literature have shown that the EM field travels in conductive mediums obeyed the diffusion equations [4, 8, 1]. The EM field excited by a horizontal electric dipole (HED) or a horizontal magnetic dipole (HMD) travels in sea water and seafloor strata at different velocities. The HED can generate both galvanic effects currents and inductive effects currents, so it is sensitive to thin resistive layers, and inline dipole-dipole configuration is the main surveying system, and works with multi offsets. The electromagnetic response of resistive hydrocarbon reservoirs measured at seafloor is a frequency dependent function of source-receiver offsets and seafloor conductivity [5, 6, 4, 1]. Multi receiver dipoles and transmitter dipoles can be laid in line with different offsets, and source signal can be a wideband low frequency due to electromagnetic (EM) attenuation in conductive sea water. According to the different diffusion velocity of the EM energy in the sea water and in the seafloor strata, the impulse response of electric field or magnetic field measured at some offsets would have two separated arrive peak time. In marine, the first peak time can be used to map the seafloor strata electricity property distribution.

In this paper we computed the impulse response of uniform half space, marine double half space and four-layer reservoir-bearing seafloor earth models to horizontal electric dipole source, so that it is helpful to choose the measure methods, measure parameters and explaining methods to the high resolution exploring hydrocarbon reservoir.

2. METHOD
The step response and impulse response to the horizontal electric dipole source in the uniform half space, marine double half space and reservoir-bearing seafloor models have analytic expressions in frequency domain [5, 4, 9]. Firstly to get time domain step response from the frequency analytical form or numerical solution through the use of Gaver-Stehfest inverse Laplace transforms and numerical Hankel transform, and then to get the earth impulse response through differential of step response. The inline electrical dipole-dipole configuration is selected.
3. NUMERICAL RESULTS

3.1. Transient Response of the Homogeneous Earth Model

In the inline electrical dipole-dipole configuration, the electric field radial horizontal component of frequency domain on homogeneous half space earth model is listed:

\[
E(\omega)|_{\phi=0^\circ} = \frac{P_E}{2\pi\sigma_1 r^3} \left[ 1 + (1 + k_1 r) e^{-k_1 r} \right]
\]

(1)

To the later field (frequency equals to 0), it is:

\[
E(0)|_{\phi=0^\circ} = \frac{P_E}{\pi\sigma_1 r^3}
\]

(2)

where \(P_E = P_{E0} e^{-i\omega t}\) is electric dipole polar moment, \(r\) is transmitter-receiver (T-R) separation, \(\sigma_1\) is the homogeneous earth conductivity, and \(k_1\) is the homogeneous earth wave number with \(k_1^2 = i\omega\mu_0\sigma_1\). The normalization of later electric field is as following:

\[
\frac{E(\omega)}{E(0)}|_{\phi=0^\circ} = \frac{1}{2} \left[ 1 + (1 + k_1 r) e^{-k_1 r} \right]
\]

(3)

With the Equation (3) divided by Laplace variation \(s = i\omega\), and then by Gaver-Stehfest inverse Laplace transforms, we can get the step response of homogeneous earth as following:

\[
e(t) = \frac{\ln 2}{t} \sum_{i=1}^{N} K_i \frac{E(\rho_n, h_n, s_i)}{s_i}
\]

(4)

The parameter \(K_i\) is the \(N\) number G-S inverse conversion coefficient during the computation \(N = 14\), with \(s_i = \frac{\ln 2}{t} i\), \(i = 1, 2, \ldots, N\) to replace \(s = i\omega\) and \(E(\rho_n, h_n, s_i)\) is electrical field response in frequency domain, \(\rho_n, h_n\) is the layer coefficient. Fig. 1 is the result of step response in (a) and impulse response in (b) of homogeneous earth with different resistivity, the T-R space \(r = 300\) m, earth resistivity is \(0.1\ \Omega\cdot\text{m}, 1\ \Omega\cdot\text{m}, 6\ \Omega\cdot\text{m}, 30\ \Omega\cdot\text{m}, 100\ \Omega\cdot\text{m}, 700\ \Omega\cdot\text{m}, 1800\ \Omega\cdot\text{m}\), respectively. In the computation, there is no consideration of EM energy of the air transmission. It is shown that the impulse response peak value will appear ahead of time with the resistivity increasing, we give the reach time of the impulse response peak a name as transient impulse time which changes with the resistivity of earth.

Figure 1: Step response (a) and impulse response (b) of homogenous half space with different resistivity.

With the Equation (3) divided by Laplace variation \(s = i\omega\), and then by Gaver-Stehfest inverse Laplace transforms, we can get the step response of homogeneous earth as following:

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e(t) = \frac{\ln 2}{t} \sum_{i=1}^{N} K_i \frac{E(\rho_n, h_n, s_i)}{s_i}
\]

(4)
3.2. Transient Response of Double Half Space Model

When the conductivity of sea water is much larger than the conductivity of the seafloor strata, the analytical form of radial electric field response to homogeneous double half space model in frequency domain in inline configure is as following [5]:

\[ E(s) \bigg|_{\varphi=0^\circ} = \frac{j(s)}{2\pi\sigma_0 r^3} \left[ (\sqrt{\tau_0 s} + 1)e^{-\sqrt{\tau_0 s}} + (\tau_1 s + \sqrt{\tau_0 s} + 1)e^{-\sqrt{\tau_1 s}} \right] \]

(5)

where parameter \( \tau_i = \frac{r^2 \mu_0 \sigma_i}{2} \) is the EM energy diffusion time coefficient of the sea water or seafloor strata, \( s = i\omega \) is the Laplace variable, \( r \) is T-R space, \( \sigma_0 \) is the conductivity of sea water and \( j(s) = PE_0 e^{-st} \) is the electric dipole polar moment. The normalization of the later electric field is as following:

\[ \frac{E(s)}{E(0)} \bigg|_{\varphi=0^\circ} = \frac{1}{2} \left[ (\sqrt{\tau_0 s} + 1)e^{-\sqrt{\tau_0 s}} + (\tau_1 s + \sqrt{\tau_0 s} + 1)e^{-\sqrt{\tau_1 s}} \right] \]

(6)

Figure 2: Transient response of double half space with different conductivity (\( \sigma_0/\sigma_1 \geq 1 \)).

In Fig. 2 we have computed the step response (a) and impulse response (b) with offset \( r = 500 \) m, when the ratio of \( \sigma_0/\sigma_1 \) is 1, 3, 10, 30, 100, 300, 1000, respectively. The impulse response has two peak reach time, the first peak indicates the EM energy travel through the resistive seafloor reaches receiver firstly, which is related to the seafloor conductivity. The two distinct impulse peak separation in time is increased with the conductivity contrast between sea water and seafloor crust.

In Fig. 3 we have computed the EM transient response of homogeneous double half space model when the seawater conductivity is 3.2 S/m, and the seafloor strata conductivity is less than 300 times than seawater conductivity. The first peak value in the figure designates the transient impulse time when the EM energy travels through the seafloor strata; the second smaller peak value designates the transient impulse time when the EM energy travels through the seawater with high conductivity. This fact explains that the transient impulse time is the function of offsets, and it will be increasing with the offsets increasing.

3.3. Transient Response of the Marine Bedded Formation Model

Suppose the thickness of layers is \( d_1, d_2, d_3, \ldots, d_{N-1} \), respectively and the conductivity of layers is \( \sigma_1, \sigma_2, \ldots, \sigma_N \), respectively, \( d_0 \), \( \sigma_0 \) is the depth and conductivity of seawater, \( \mu_0 \) is the magnetic permeability, and \( r \) is the transmitter-receiver separation. Edwards (2005) has given the radial EM response of horizontal electric dipole source as follows:
When the initial condition is zero, the Laplace transforms ($s = i\omega$) of the receiver measured electric field is as following:

$$E(s) = \frac{j(s)}{2\pi} [F(s) + G(s)]$$  

(7)

where $j(s)$ is electric dipole polar moment of electric dipole length $\Delta L$, the current step on with current is $I$ (Ampere) at $t = 0$, and the Laplace transforms of the dipole moment as follows:

$$j(s) = \frac{I\Delta L}{s}$$  

(8)

To axial dipole, $F(s)$ and $G(s)$ are Hankel transforms:

$$F(s) = -\int_0^\infty \frac{Y_0 Y_1}{Y_0 + Y_1} \lambda J_1'(\lambda r) d\lambda$$  

(9)

And

$$G(s) = -(s/r) \int_0^\infty \frac{Q_0 Q_1}{Q_0 + Q_1} J_1(\lambda r) d\lambda$$  

(10)

where $J_1$ is the first order Bessel function in first class, and $\lambda$ is the Hankel integration variable, and in the equations:

$$Y_0 = \frac{\theta_0}{\sigma_0} \left[ \frac{\sigma_0 u_a + s\varepsilon_0 \theta_0 \tanh(\theta_0 d_0)}{s\varepsilon_0 \theta_0 + \sigma_0 u_a \tanh(\theta_0 d_0)} \right]$$  

(11)

And

$$Q_0 = \frac{\mu_0}{\theta_0} \left[ \frac{\theta_0 + u_a \tanh(\theta_0 d_0)}{u_a + \theta_0 \tanh(\theta_0 d_0)} \right]$$  

(12)

where $\theta_0^2 = \lambda^2 + s\mu_0$ is the wave number of seawater, $u_a^2 \approx \lambda^2$ is the wave number of air, and $Y_1, Q_1$ are layers’ parameters of seafloor, respectively. Recursion according to following equation:

$$Y_i = \frac{\theta_i}{\sigma_i} \left[ \frac{\sigma_i Y_{i+1} + \theta_i \tanh(\theta_i d_i)}{\theta_i + \sigma_i Y_{i+1} \tanh(\theta_i d_i)} \right]$$  

(13)

And

$$Q_i = \frac{\mu_0}{\theta_i} \left[ \frac{\theta_i Q_{i+1} + \mu_0 \tanh(\theta_i d_i)}{\mu_0 + \theta_i Q_{i+1} \tanh(\theta_i d_i)} \right]$$  

(14)
where $\theta_2^2 = \lambda^2 + s\mu\sigma_1$, $Y_N = \theta_N/\sigma_N$ and $Q_N = \mu_0/\theta_N$. If the depth of seawater is more than the T-R space of $r$, it is simplified as $Y_0 = \theta_0/\sigma_0$ and $Q_0 = \mu_0/\theta_0$; and if the seafloor strata is homogeneous within the T-R space $r$, it is simplified as $Y_1 = \theta_1/\sigma_1$ and $Q_1 = \mu_0/\theta_1$.

To get the impulse response of layered reservoir-bearing seafloor model, we need to compute the Hankel transforms in Equations (9) and (10) like form in Equation (15). This paper adopts the direct computation numerical integration method to compute the Hankel transform, and the kernel function is dealt with subtracting the homogeneous double half space kernel function, and then use the integration result plus the homogeneous double half space analytical solution.

$$f(r, P) = \int_0^{\infty} K(\lambda, P)J_n(\lambda r) d\lambda$$

In Fig. 4(a) we have shown the impulse response computation results of multi T-R space of the model in Fig. 4(b) with the depth of seawater is $d_0 = 2000$ m, and resistive N2 layer is interbedded between more conductive layers N1 and N3, the T-R space $r$ changes from 1200 m to 3200 m, interval is 100 m. During the computation we use the logarithm of both time and T-R space. It is clearly to find that the first impulse peak time changed at appropriated offsets with resistive hydrocarbon present. The existence of resistive structure largely influence the first transient impulse peak time which travels through the seafloor. It is also suggested that surveying with multi-offsets can detect thin resistive layer.

4. CONCLUSION

The numerical computation results showed that impulse response transient time of earth system can indicates the electrical property of the earth. Electromagnetic attenuation in seawater is the function of both frequency and T-R space, and we should adopt the multi offsets electric dipole-dipole survey system and choose the wide frequency band signal source which we can measure the biggest impulse response of resistive hydrocarbon in both appropriated frequency and offsets. Moving the set array can complete the profile measurement and sounding measurement. And it has high resolution to the thin resistive subsurface formations, therefore this method can be applied for hydrocarbons explorations on land, also in marine.

REFERENCES


