Reservoir Characteristics Classification using Acoustic Signal Processing

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Abstract

Reservoirs are losing its capacity due to various materials getting dumped after every rainy season. So in order to estimate the reservoir capacity and to plan the reservoir operations, the modelling process is defined to represent idealization of reservoir by a mathematical model using governing equations. Then using acoustic signals the underwater sediments are classified. In this paper reservoir model is created using finite volume. The finite volume method falls into the family of Godunov algorithms and is a technique for solving a system of hyperbolic equations. This method is considered very accurate as it conserves mass at every time step. It operates by updating the solution within some control volume and includes all the inter-cell mass and momentum flux contributions in a single step. Then acoustic signal is transmitted through the reservoir model. Then different features are extracted from the reflected signals and the reservoir characteristics such as stone, gravel, sand, silt, clay are classified.
Keywords: Sediment Classification, Finite Volume Method (FVM), Reservoir Characterization, Underwater Acoustics

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I. INTRODUCTION

Reservoir characterization involves reservoir modeling and reservoir sediment composition classification. Reservoir model can be created using shallow water equations. These are generally hyperbolic equations. Finite Volume method is established method for solving hyperbolic equations. The attractiveness of this method comes from being adequately robust, highly accurate and is not restricted to rectangular solution grids. To develop the equations which describe a flow, it is assumed that fluids adhere to fundamental law of physics i.e. the law of conservation of mass and conservation of momentum. In this method the mass is conserved at every time step. It operates by updating solution at with some control volume and includes all the inter- cell mass and momentum flux contributions in a single step. Then the acoustic signal is transmitted through the reservoir in order to classify the underwater sediments. Acoustic signal processing techniques are most suitable techniques for underwater applications as acoustic signals can travel over long distances in water than electromagnetic signals.

For centuries, since the European started exploring the oceans, hydrographs used manual measurement systems like chronometers, sextant fixes and lead lines, to produce nautical maps, which were key in determining safe shipping routes. In the beginning of the 20th century the acoustic systems were developed for measuring ocean depths and for obstacle detection. These were active systems, emitting and recording sound, and were called SONAR (Sound Navigation and Ranging). These devices consist of one source and one recording unit i.e. a hydrophone. Such systems are now known as single beam eco-sounders. In the second half of the 20th century eco-sounders became more accurate and other types became available, such as the side-scan sonar and the multi-beam eco-sounder. For classification of reservoir characteristics it is required to determine the depth as well as sediment composition of the reservoir. Classification of reservoir characteristics can be performed using two approaches, the empirical and the model based methods. Instead of classifying the reservoir characteristics on the actual reservoir using empirical method, the model based approach is used where the model of the reservoir is created using Finite volume method and simulated using Matlab. Then the underwater objects are classified based on the acoustic reflected signals.

II. RESERVOIR MODEL USING FINITE VOLUME METHOD

To perform the classification of reservoir characteristics using a model based approach, it is first necessary to define the modeling process to represent the idealization of the physical i.e. reservoir by a mathematical model, using governing equations of the problem. There are various physical phenomena which can be represented by a different numerical solutions obtained from solving partial differential equations (PDEs). PDEs are mathematical models of continuous physical phenomenon in which dependent variable say u, is a function of more than one independent variable, say t (time) and x (e.g. spatial position). PDEs derived by applying a physical principle such as conservation of mass, momentum and energy. The Numerical solutions of these PDEs can be obtained from three methods, the finite difference method (FDM), finite volume method (FVM) and finite element method (FEM). In this paper Finite volume method is used to create the mathematical model of reservoir. Rather than point-wise approximations on a grid, FVM approximates the average integral value on a reference volume, which means instead of breaking the model it to discrete cells; we break the model into discrete volumes. The main advantages of this method are that it can handle Non- Cartesian geometries which are required for most natural circumstances. It can handle subcritical and supercritical boundaries with only minor adjustments. Hence FVM appears very promising approach to create the mathematical model of reservoir. Shallow water equations are used to create reservoir model and these are generally hyperbolic equations. The Finite Volume Method is an established method of solving hyperbolic equations. The attractiveness of this method comes from being adequately robust, highly accurate and is not restricted to rectangular solution grids. The grids can be irregularly shaped channel geometries which have large variations in profile. If this profile were fitted with the standard rectangular grids. It can be very hard to fit grids which cover all of the channel bed. This leads to various other shaped cells, e.g. triangular, which can be made to fit almost any channel bed no matter the So FVM is found to be best suitable method to create reservoir model.

$$\frac{\partial}{\partial t}\int_{\Omega} U\, d\Omega + \int_{\Omega}(Fdx - Gdy) = \int_{\Omega} S d\Omega \qquad (1)$$

Where U is the vector of flow variables, F and G are fluxes and S is the source term induces because of bed slope, frictional slope The FVM falls into the family of Godunov-type algorithms and is a technique for solving system of hyperbolic equations [3]. This method is considered very accurate as it conserves mass at every time step. It operates by updating the solution with some control volume and includes all the mass and momentum fluxes. Here FVM is used as the variation of the Godunov algorithm instead of breaking the model into discrete volumes. The main advantages of this method are that it can handle Non-Cartesian geometries which are required for most natural circumstances. It does not to generate and remove cells around wetting and drying boundaries. It can handle supercritical and subcritical boundaries with only minor adjustments.

III. UNDERWATER SIGNAL PROPAGATION AND LAYER CLASSIFICATION

Acoustic signals are the most suitable signals used in the underwater as they can propagate over long distances. To realize the mechanism of acoustic signal propagating through underwater layer media a computer simulation program is developed for accounting attenuation effects. A seven layer underwater structure is assumed based on the data given in Table (1). The input signal x (t) as a representative of a typical seismic source signature analytically expressed by [4]:

$$x(t) = 1360 * e^{-500t} - o.5 * e^{-15.3t}\sin(\omega t) \qquad (2)$$

Here t is the time and $\omega = 2\pi f$ is the frequency of the input signal x(t). In reflection seismology a source of energy produces a signal x(t) applied close to or on the water surface in reservoir. Mathematically, if the experiment is represented by a lossless wave equation, then all the signals within the media will be the time delayed scaled replicas of the source signal, x(t).Let y(t) be the resulting output signal of the model given by :

$$y(t) = \sum_{i=0}^{N} A_i * x(t - \tau_i) \qquad (3)$$

Here τ_i are the time delays and A_i are frequency dependent medium amplitude scale factors that vary with layer thickness and defined by

$$A_i = \alpha_i * e^{-\omega D_i} \qquad (4)$$

Where α_i frequency independent amplitude scales factors and are the media damping factors then the Eq.(3) becomes,

$$y(t) = \sum_{i=0}^{N} \alpha_i * e^{-\omega D_i} * x(t - \tau_i) \qquad (5)$$

Seven layer is simulated to find the value of y(t),using convolution model given by Eq.(3) The model parameters are listed in Table I. Using the media characteristics and defined the input signal, the synthetic observation data in the layers is obtained. These waveforms indicate that the amplitude of the output signals is affected by the attenuation parameters of each sediment type.

Table – 1
Material Characteristics

Material	α_i *(mV)*	g_i *(mm)*	a_i *(db/ft)*	d_i *(ft)*	τ_i *(ms)*
Silty Sand	*0.061*	*0.10*	*2.80*	*27*	*0.20*
Fine Sand	*0.063*	*0.18*	*7.00*	*45*	*0.56*
Very Fine Sand	*0.051*	*0.09*	*4.50*	*48*	*0.74*
Sand-Silty Clayey	*0.032*	*0.03*	*7.30*	*56*	*0.80*
Medium Sand	*0.046*	*0.60*	*3.60*	*62*	*1.40*
Coarse Sand	*0.041*	*0.30*	*2.90*	*64*	*2.60*
Clayey Silt	*0.015*	*0.01*	*2.07*	*72*	*2.62*

IV. TRANSMISSION LOSS OF SOUND OF WATER

A. Spreading Loss:

Spreading loss is a measure of signal weakening due to the geometrical spreading of a wave propagating outward from the source. Two geometries are of importance in underwater acoustics, spherical spreading i.e. a point source in an unbounded homogeneous medium and cylindrical spreading. i.e. a point source in a medium that has upper and lower boundaries .If medium is assumed to be lossless then intensity for spherical spreading is inversely proportional to the surface of radius r, i.e.

Spherical Spreading loss = I a / 4Πr^2 (6)

Where I is the intensity and a is the distance traveled by the signal. For cylindrical spreading inversely proportional to the surface radius r and depth d,

Cylindrical Spreading = Ia/(2Πrd) (7)

B. Sound Attenuation in Water:

The acoustic energy of a sound wave propagating in the water is partly absorbed, i.e. the energy is transformed into heat and lost due to sound scattering by in homogeneities. Thus sound attenuation in water is given by,

$$a_w = 8686 \left(\frac{SAf_Tf^2}{f_T+f^2} + \frac{Bf^2}{f_T}\right)(1 - 6.54{*}\ 10^{-4}) \quad (8)$$

Where A= 2.34 X 10^{-6}, B=3.38 X 10^{-6}, S= Salinity [ppt], f is frequency of the input signal and f_T is the frequency of the signal traversed through each layer or signal reflected by the object.

C. Sound Attenuation in Sediment:

The sound attenuation in the sediment mainly varies with the bottom type. So it can be used to determine sediment type. It can approximately determine by the empirical formula as,

$$\alpha_w = \frac{1}{8.686} K\left(\frac{f}{1Khz}\right)^n \quad (9)$$

Where K and n denote two bottom type dependent parameters which are given table below,

Table – 2
Values of K and n for different sediment type

Parameter	*Sediment type*				
	Clay	*Silt*	*Sand*	*Gravel*	*Stone*
K	*0.17*	*0.45*	*0.48*	*0.53*	*0.75*
N	*0.96*	*1.02*	*0.98*	*0.96*	*0.99*

D. Forward Reflection Loss:

A rough water surface causes attenuation of the acoustic field propagating in the water waveguide. The attenuation increases with increase in frequency. The field is scattered away from the specular direction. The forward reflection loss due to a rough boundary is often simply modeled by incorporating an additional loss factor into the calculation of the reflection coefficient. A formula often used to describe reflectivity from boundary is:

$$R(\varphi) = R(\varphi)e^{-\frac{p^2}{2}} \quad (10)$$

and

$$p(\varphi) = 2k\sigma cos\varphi \quad (11)$$

where k = $\frac{2\Pi}{\lambda}$ with the wavenumber, λ= $\frac{c}{f}$ and σ *is the* RMS (root mean square) roughness and φ the angle of incidence. The following table provides the value of mean grain size and the RMS roughness for various sediment types. P is the power of the signal.

Table – 4
Values of mean grain size and surface roughness w. r. t. sediment type

Sediment type	*Mean Grain Size* [φ = −log2 (a)]	*RMS Roughness* σ *[cm]*
Sandy Gravel	*-1*	*2.50*
Very coarse sand	*-0.5*	*2.25*
Medium sand	*0.5*	*1.85*
Fine sand	*1.5*	*1.45*
Very fine sand	*2.5*	*1.15*
Coarse Silt	*3.5*	*0.85*
Medium Silt	*4.5*	*0.7*
Fine Silt	*5.5*	*0.65*
Very fine silt	*6.5*	*0.60*
Silty clay	*7.5*	*0.55*
Clay	*8*	*0.50*

V. CONCLUSION

Classification of the reservoir sediments can be done using two approaches i.e. empirical and model based approach. The empirical approach is commonly used this method uses bottom samples to classify the sediments but the drawback of this method is that it is slow and expensive. The model based approach in principle eliminates the need of bottom samples. Here a theoretical model is used to predict the signal and then depending on the material characteristics and the reflected acoustic signals the sediment is classified. The model produces the range of that can correlate to the actual received signal. Hence the model based approach is used to classify the reservoir sediments which are done by extracting features from received signals. The features are found to vary depending on the sediment type.

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