Development of an analytical model to predict oil reservoirs performance using mechanical waves propagation

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ABSTRACT

The mechanical waves have been used as an unconventional enhanced oil recovery technique. It has been tested in many laboratory experiments as well as several field trials. This paper presents a robust forecasting model that can be used as an effective tool to predict the reservoir performance while applying seismic EOR technique. This model is developed by extending the wave induced fluid flow theory to account for the change in the reservoir characteristics as a result of wave application. A MATLAB program was developed based on the modified theory. The wave's intensity, pressure, and energy dissipation spatial distributions are calculated. The portion of energy converted into thermal energy in the reservoir is assessed. The changes in reservoir properties due to temperature and pressure changes are considered. The incremental oil recovery and reduction in water production as a result of wave application are then calculated. The developed model was validated against actual performance of Liaohe oil field. The model results show that the wave application increases oil production from 33 to 47 ton/day and decreases water-oil ratio from 68 to 48%, which is close to the field measurements. A parametric analysis is performed to identify the important parameters that affect reservoir performance under seismic EOR. In addition, the study determines the optimum ranges of reservoir properties where this technique is most beneficial.

Keywords: Downhole Seismic Tools; In-Situ Seismic; Mechanical Waves; Seismic EOR

INTRODUCTION

Since 1954, many theories have been developed to understand the full image of elastic wave propagation through saturated elastic porous media. The first formulation of elastic wave propagation in porous media was postulated by Biot (1965a, 1965b). He developed a theory for the propagation of stress waves in a porous elastic solid media saturated by a viscous fluid.

Later, and starting from the early 1980's until now, the interest in applying elastic wave stimulation was focused mainly on acoustic and to a lower degree on surface vibrators. In the late 1990's, a third type of elastic wave stimulation (in-situ seismic stimulation) was developed. The mechanism is to create a high-energy elastic wave identical to earthquakes but at reservoir depth (in-situ) and lower magnitudes so as not to destroy the reservoir (Kostrov & Wooden, 2008). Extensive field studies using downhole seismic stimulation have proven to increase oil production and oil recovery.

The theories developed after Biot addressed the limitations of this theory's assumptions. These theories extended Biot's theory to cover all frequency ranges and two-phase flow type (Brutsaret, 1964), double-porosity effect (Ba et. al., 2011), squirt flow model (Mavko & Jizba, 1991; Chapman et. al., 2002), saturation fluid effect (Calvert, 2005), patchy saturation effect (Mavko & Mukerji, 1998), and the use of spatially varying coefficients (Müller & Gurevich, 2005a; Müller & Gurevich, 2005b)

These theories rely on some restricting assumptions limiting their application. The common assumptions: (1) homogeneous reservoir, (2) one-dimensional wave flow propagation, (3) single-phase fluid, and (4) no thermo-elastic effects. In addition, the main problem of these theories is that it focuses on the wave properties and ignores the wave's subsequent effects on reservoir properties. They also ignore the changes in reservoir performance resulting from wave application.

On the other hand, the literature includes several recent laboratory studies which have been performed to study the effect of acoustic waves on the hydrocarbon properties and flow behavior in porous media (Hamidi et. al., 2014; Hamidi et. al., 2015; Louhenapessy & Ariadji, 2020; Khasi et. al., 2021).

In this paper, a model is developed by combining multidiscipline scientific branches to predict the reservoir performance while applying seismic EOR technique. Wave motion and propagation in rocks and its energy distribution and dissipation or attenuation is studied. In addition, the wave induced fluid flow theory is modified to consider the changes in reservoir characteristics caused by exposing the reservoir to mechanical waves. The model calculates the spatial distribution of the wave's intensity, pressure, and energy dissipation. Moreover, it assumes that the portion of energy dissipated to the reservoir is converted into thermal energy. The developed model can calculates the change in reservoir properties due to temperature and pressure changes. The incremental oil recovery and reduction in water production as a result of wave application is then calculated. A simple MATLAB program is developed to implement this analytical model.

MECHANICAL WAVES STIMULATION MECHANISM

There are several possible mechanisms that attempt to explain oil extraction from porous media under the effect of high energy elastic waves. These waves cause mechanical disturbance in the reservoir fluids while they move. The mechanical disturbance continues to consume the wave power until relaxation occurs. High energy elastic waves introduce mechanical vibrations, which strongly influence interfacial and viscous forces by enhancing momentum and heat transfer across the phase interfaces. These effects are believed to be responsible for the observed improvement in percolation of oil within porous media (Hamida & Babadagli, 2005; Hamida & Babadagli, 2007). These effects strongly depend on the elastic wave's frequency and intensity. Intensity defines the wave strength and quantifies both the wave mechanical and thermal impacts. Frequency plays an important role in wave dispersion, attenuation, and penetration profile into the formation.

MODEL FORMULATION

A reliable theory that applied the method of statistical smoothing to Biot's poroelasticity equations in a random, heterogeneous, porous medium has been developed and named the wave induced fluid flow theory (Müller & Gurevich, 2005a; Müller & Gurevich, 2005b). The fast and slow P-wave velocities, inverse quality factor, attenuation, and propagation schemes are derived assuming that the reservoir consists of a single homogeneous background rock type with small discrete patches of other rock types. The statistical smoothing method is used to account for these discrete patches, the spatial distribution of these rocks is modeled by a

unified spatial correlation function B(r). This function is the variance of the random relative fluctuations in rock properties. All poroelastic parameters assumed to have the same unified spatial function and correlation length. The effective P-wave number $\bar{K}_P$ is derived to be:

$$\bar{K}_P = K_P \left(1 + \Delta_2 + \Delta_1 K_{Ps}^2 \int_0^\infty rB(r)\exp(irK_{Ps})dr \right)$$
Eq. 1.

Where the dimensionless coefficients Δ_1 and Δ_2 are given by:

$$\Delta_1 = \frac{\alpha^2 M}{2P_d}\left(\sigma_{HH}^2 - 2\sigma_{HC}^2 + \sigma_{CC}^2 + \frac{32\,G^2}{15\,H^2}\sigma_{GG}^2 - \frac{8\,G}{3\,H}\sigma_{HG}^2 + \frac{8\,G}{3\,H}\sigma_{GC}^2 \right)$$
Eq. 2.

$$\Delta_2 = \Delta_1 + \frac{1}{2}\sigma_{HH}^2 - \frac{4\,G}{3\,H}\sigma_{HG}^2 + \left(\frac{4G}{H} + 1\right)\frac{4\,G}{15\,H}\sigma_{GG}^2$$
Eq. 3.

Where
$$B(0) = 1 \qquad\qquad B(\infty) = 0$$

$$K_{Ps} = \sqrt{i\omega\mu/(k_0 N)} \qquad\qquad H = P_d + \alpha^2 M$$

$$M = \left[(\alpha - \phi)/K_0 + \phi/K_f\right]^{-1} \qquad\qquad \alpha = 1 - K_d/K_0$$

$$N = MP_d/H \qquad\qquad C = \alpha M$$

Expressions for velocity dispersion $V(\omega)$ and attenuation or inverse quality factor Q^{-1} are obtained from the real and imaginary parts of the effective wavenumber:

$$V(\omega) = \frac{\omega}{Re\{\bar{K}_P\}} = V_0 \left(1 - \Delta_2 + 2\Delta_1 K_{Psr}^2 \int_0^\infty rB(r)\exp(-rK_{Psr})\sin(rK_{Psr})dr \right)$$
Eq. 4.

$$Q^{-1}(\omega) = \frac{2Im\{\bar{K}_P\}}{Re\{\bar{K}_P\}} = 4\Delta_1 K_{Psr}^2 \int_0^\infty rB(r)\exp(-rK_{Psr})\cos(rK_{Psr})dr$$
Eq. 5.

Where
$$V_0 = \sqrt{H/\rho} = constant \qquad\qquad K_{Psr} = \sqrt{\omega\mu/(2k_0 N)}$$

The limitation of this model is that it homogenized the whole reservoir into a single rock type by using the statistical smoothing approach. In addition, all the previous wave-propagation theories are studied for earthquakes and petroleum exploration modeling purposes. They did not consider the wave effects on the reservoir fluids. They only focused on the wave propagation, intensity, and strength. The purpose of this study is to modify Müller and Gurevich's model and extend it to account for the effect of the wave on reservoir

rock and fluid properties. In addition, it takes into consideration the wave energy effects on enhancing petroleum reservoirs performance.

The following modifications are applied to the original Müller and Gurevich's model in order to simulate and forecast the reservoir performance under the application of the seismic wave EOR technique:

1. *Wave Attenuation Calculations in dB:* The quality factor, Q, is a measure of the material resistance to wave propagation. The quality factor describes how strong the wave is. The attenuation coefficient or the attenuation rate $(\bar{\alpha})$ is a function of the quality factor and the wavelength (Wang, 2008). The wave attenuation at any location *r* away from the wave-source center is calculated as shown in Eq. 6.

$$Attenuation = \bar{\alpha} * r = \frac{Q^{-1}*(27.3)}{\lambda} * r = \frac{Q^{-1}*(27.3)}{(2*\pi*V)/\omega} * r \quad \text{(dB)} \qquad \text{Eq. 6.}$$

2. *Wave intensity and Pressure Distribution Calculations:* Seismic waves transport energy from one point to another through a transporting medium that acts as the resistance medium to the wave propagation and successively consumes its energy until the wave vanishes. Seismic quantities such as intensity or pressure are usually quantified on a logarithmic scale and measured by decibels (dB). The wave intensity and pressure at any point with reference to that at 1m from the wave source as a function of wave attenuation could be expressed by Eq. 7, and Eq. 8 respectively (Lurton, 2010).

$$Intensity = Intensity_{1m} * 10^{-\left(\frac{Attenuation}{10\ (dB)}\right)} \qquad \text{Eq. 7.}$$

$$pressure = pressure_{1m} * 10^{-\left(\frac{Attenuation}{20\ (dB)}\right)} \qquad \text{Eq. 8.}$$

3. *Wellbore Losses Calculations*: The losses in the wellbore arise from the reflected part of the wave on the surface of the reservoir rock. When a wave travels from one medium (wellbore fluid) to another medium different in density (reservoir rock), the wave is divided into two parts (reflected part and transmitted part) obeying the well-known Snell's law. The transmission coefficient could be calculated using the formula expressed in Eq. 9.

$$\tau = \frac{2z_1}{z_1+z_2} \qquad \text{where} \qquad z = \rho v \qquad \text{Eq. 9.}$$

4. *Temperature Change Calculations:* Figure 1 shows a wave moving between two points 1 and 2 in the reservoir. The wave's energy decreases from original energy e_1 to the final energy e_2. Similarly, the wave's power decreases from original power P_1 to the final power P_2 starting at the original time t_1 and ending at the final time t_2. The change in wave's energy Δe is calculated and converted into heat energy which is responsible for raising the reservoir's liquids temperature as expressed in Eq. 10.
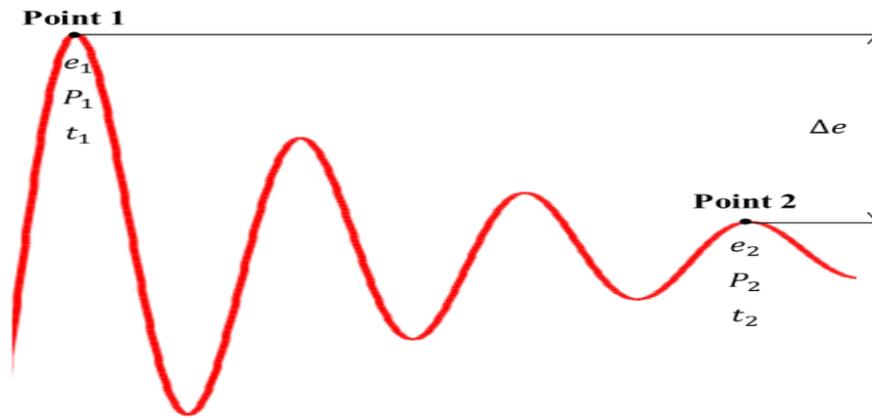
$$\Delta e = \Delta P * \Delta t \qquad \text{Eq. 10.}$$

Figure 1. Wave power/energy loss while moving from Point 1 to Point 2**.**

Energy added to the reservoir is converted to heat energy following the principle of energy conservation. Heat energy raises the reservoir fluid temperature following the well-known heat transfer equation (Eq. 11).

$$q_{th} = mc\Delta T \qquad \text{Eq. 11.}$$

Applying the energy conservation principle (the energy lost from the wave is equal to the energy added to the reservoir), Eq. 12 is composed.

$$\Delta e = \Delta P * \Delta t = q_{th} = mc\Delta T \qquad \text{Eq. 12.}$$

Then, convection heat transfer from reservoir fluid to reservoir rock occurs following the convective heat transfer given by Eq. 13.

$$q_{th} = h_c A\Delta T \qquad \text{Eq. 13.}$$

Mass and heat balance need to be checked at every grid block for every time step. At each time step, a certain mass of fluid exits, and the rest of the grid block fluid mass remains, while another mass is added.

Mass balance is applied as in Eq. 14. Heat balance (thermal equilibrium) is applied taking into consideration the mass balance for the grid block.

$$\text{Final fluid mass} = \text{added fluid mass} + \text{remaining fluid mass} \qquad \text{Eq. 14.}$$

Thermal losses occurred at reservoir boundaries through conduction to overburden and underlying rock layers. The thermal energy flow rate is calculated using Fourier's law which is expressed in Eq. 15.

$$q_{th} = -\Lambda\, A\, \frac{\Delta T}{d} \qquad \text{Eq. 15.}$$

The thermal flow rate calculated in Eq. 15 is deducted from the reservoir thermal energy and added to the overburden and underlying rock layers' thermal energy. The final reservoir rock and fluid temperature is calculated based on the deducted thermal energy.

5. *Flow Rate Calculations:* Based on the data provided by Arps (1956), a correlation that relates the residual oil saturation with the oil viscosity both under reservoir conditions is established as presented in Eq. 16 with R-squared value of 0.9983.

$$S_{or} = 3.9201 * Ln(\mu_o) + 34.487 \qquad \text{Eq. 16.}$$

Decreasing oil viscosity causes some of the residual oil saturation to become mobile, which increases oil recovery. In addition, it increases the mobility of oil relative to that of water, which accelerates the recovery and decreases the water cut. Wave propagation through the reservoir changes two parameters in Darcy's equation (Eq. 17). It decreases capillary pressure by acting against it with a value of the wave pressure p_{wave}. In addition, it decreases the oil viscosity μ_o. These two effects increase the flow rate and the reservoir recovery. The effect of wave pressure on capillary pressure was modeled by assuming that the wave pressure p_{wave} must exceed the value of capillary pressure to be able to free the oil droplet from the holding capillary forces. The temperature effect was assumed in the model by updating oil viscosity value as function of temperature.

$$q = \frac{0.00708 * kh * (\bar{p} - p_{wf} - P_c)}{\mu * B * [\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s]} \qquad \text{Eq. 17.}$$

The existence of free gas at the reservoir will weaken the application of this method. The free gas will act as an air bag that absorbs the wave impact. Therefore, seismic EOR is better applied to an oil reservoir above the bubble point pressure.

PROGRAMMING AND PARAMETRIC STUDY

The developed model was programmed using MATLAB programming language. The code flowchart is presented in **Figure 2**. The code calculates the average rock and fluid properties of the grid block such as the average porosity, permeability, fluid saturations, fluid density, rock density, fluid viscosity, and bulk modulus. The code calculates the wave velocity, the wave quality factor, the wave attenuation in dB, and the wave intensity and pressure in every grid block.

To calculate the effect of the waves on production, the code calculates the energy added to the grid block at each time step, the consequent change in the grid block temperature, and the change in the grid block fluids density and viscosity. The code applies Darcy's equation and the material balance equation for fluid flow and mass conservation. All these calculations can run with and without applying the wave effects to investigate the effect of the wave application.

At the end of the run, a detailed report of the run is printed as well as an output data file. A group of figures is presented to illustrate the effect of applying the wave on the performance of the reservoir. These figures compare between the production with and without wave application.

A parametric study is conducted to investigate the effects of the wave parameters, reservoir rock and fluid properties, and wellbore fluid density. In addition, the comparison between reservoir performance with and without wave application is useful in identifying the most influential parameters on the application of seismic EOR technique. Moreover, this comparison could specify the optimum properties ranges for the application of the technique.

The parametric study shows that the most influential parameters are the wave frequency, original intensity, the wellbore fluid density, and the distance between the producing well and the wave source. In addition, reservoir initial temperature, permeability, and oil density are critical parameters. On the other hand, the average reservoir porosity is not a critical parameter. The optimum range of these critical parameters in

order to achieve the best reservoir performance under the application of high energy elastic waves as an EOR
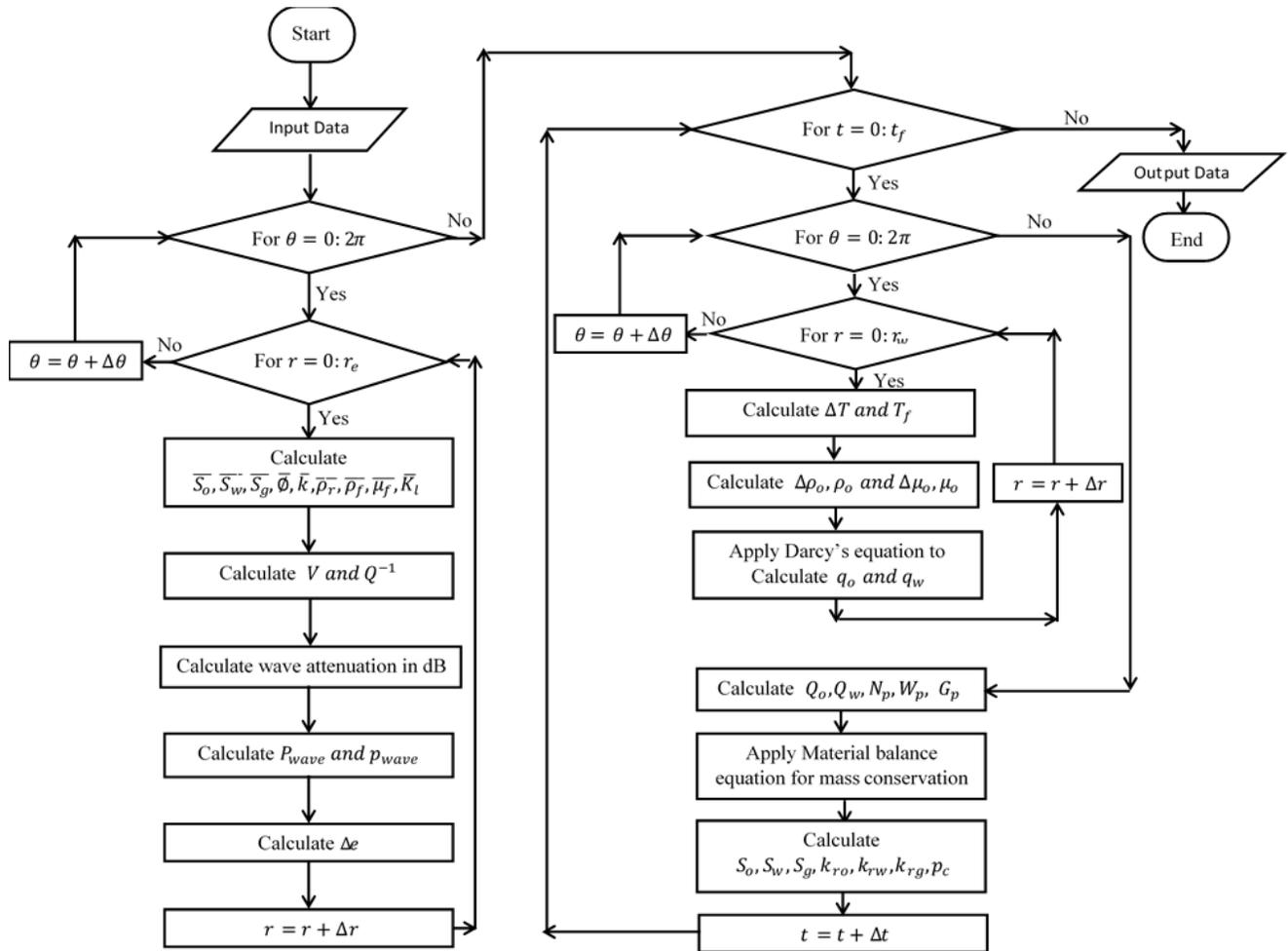
agent is listed in **Table 1.**

Figure 2. The model programming code flowchart

Table 1. The optimum range of the critical controlling parameters

Controlling Parameter	Optimum Range
Wave Frequency	100: 1000 Hz
Wave intensity	> 100 watt/m^2
Distance from Source	< 1000 m
Reservoir Permeability	> 10 md
Reservoir Oil Density	800: 1000 Kg/m^3
Initial Reservoir Temperature	< 50 ℃
Wellbore Fluid Type	High density liquids
Reservoir Porosity	Not critical

MODEL VALIDATION

Downhole seismic EOR technique was tested in Liaohe oilfield for 20 days (Zhu et. al., 2005). The developed model was used to simulate the performance of Liaohe oilfield test. The wave source and the actual reservoir parameters are used as input data for the program. The results of the program are compared with the actual test results.

It should be highlighted that the Liaohe oilfield was in late cyclic steam stimulated recovery period before applying the downhole vibration tool. The wave source was Downhole Harmonic Vibration Oil-displacement System (DHVOS) tool. The wave source performs 88 shocks per minute with each shock having 5-ton strength. The accumulated vibration test was continued for 20 days. A total of 23 oil wells were effectively influenced by the artificial seismic waves within the 300:400-meter radius around the seismic source well. The oil production increased from 36 tons/day before using the tool to 47 tons/day while applying the wave. The cumulative water cut in the stimulated area declined from 68% before using the tool to 56% while using the tool.

The developed program was run using the properties of Liaohe reservoir (**Table 2).** The results of the model are presented in **Figures 3** and **4.**

Table 2. Summary of the input data of Liaohe oilfield case

| Input Data Provided in the Original Publication by Zhu et al. (2005)		
Parameter	**Value**	**Dimensions**
Pay Thickness	67.7	m
Porosity	24	%
Permeability	2420	md
Crude oil viscosity	500	mPa.s.
Crude oil density	0.946	gm/cm^3
Wave intensity	1483	$Watt/m^2$
Wave source pressure	147	psi
Application period	20	day
Affected wells	23	well
Wells distribution radius	300: 400	m
Assumed Data		
Average reservoir pressure	914	psi
Bottomhole flowing pressure	880	psi
Reservoir temperature	23	°C
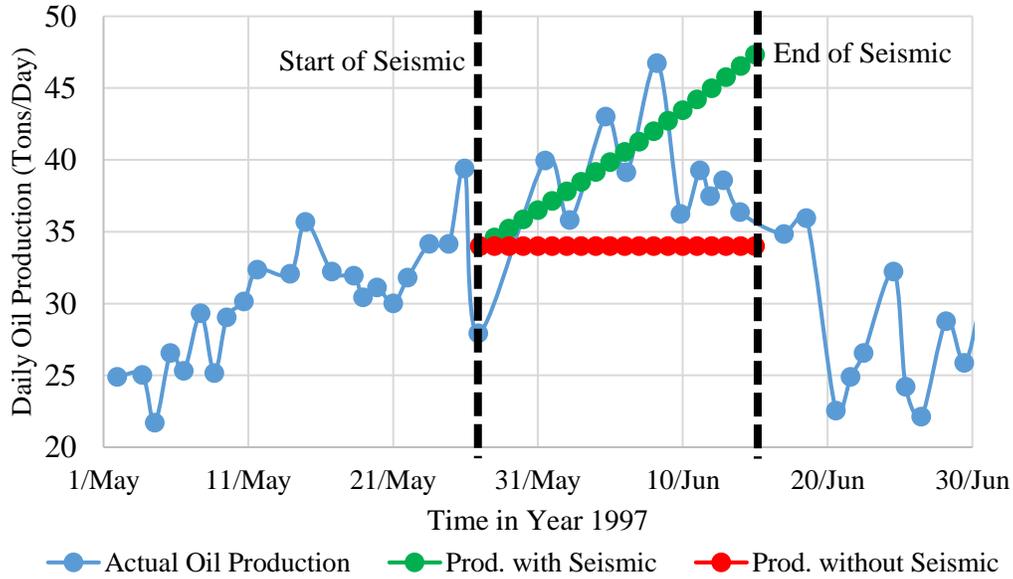
Figure 3. The daily oil production with and without the wave application using the developed model Vs Liaohe oilfield data in the range 300-400m (Total 23 wells)
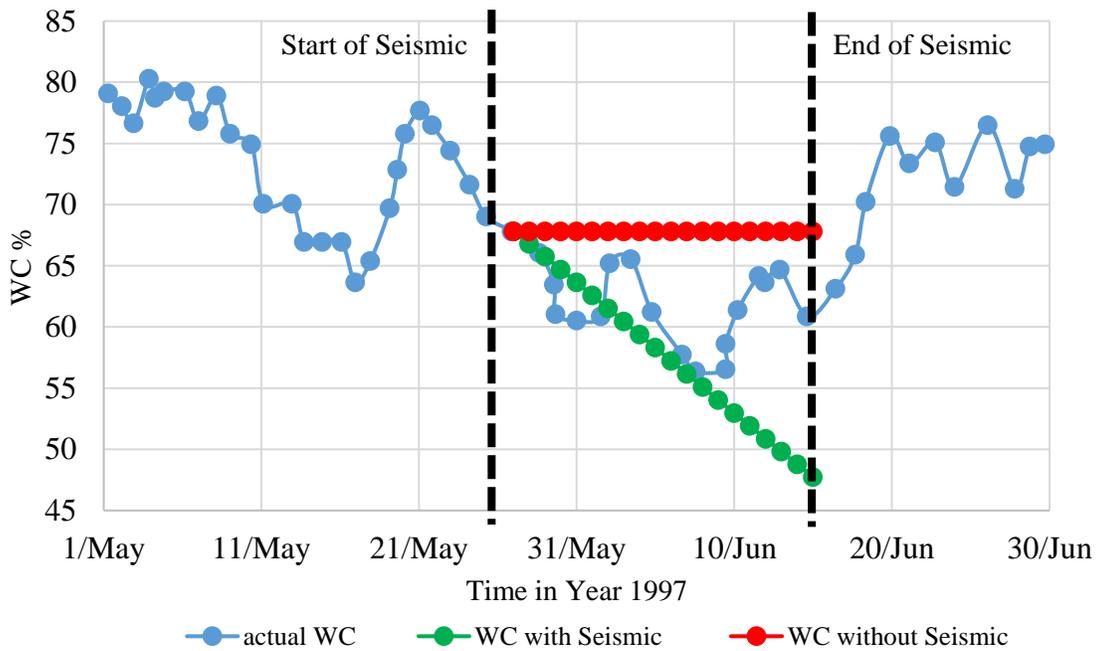

Figure 4. The water cut with and without the wave application using the developed model Vs Liaohe oilfield data in the range 300-400m (Total 23 wells)

The model application in the range of 300:400-meter radius around the wave source results in an increase in oil production rate from 33 to 47 ton/day and a decrease in the water-oil ratio from 68 to 48%. This increase

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in oil production and decrease in the water-oil ratio are relatively close to the actual field observations (actual field observation shows increase in oil production from 36 to 47 tons/day and decrease in water-oil ratio from 68 to 56%). This reasonable match verifies the reliability of the developed model.

The results of running the new developed program using Liaohe oilfield test properties shows that the wave intensity and wave pressure are exponentially decreasing at different orders with distance from the source by the act of the increasing wave attenuation. In this case, the reservoir absorbs most of the wave power and pressure around 1000m. The zone near the wave source is exposed to a very high wave pressure and absorbs most of the wave energy. Hence, zones near the wave source are expected to have the greatest improvement in the reservoir performance. These results agree with the empirical observation that downhole seismic application is only effective within a particular distance of the tool (Kostrov & Wooden, 2008).

CONCLUSIONS

1. A new model has been developed to simulate reservoir performance under the application of high energy mechanical waves.

2. The developed model was validated against actual performance of Liaohe oilfield test case.

3. The study showed that the mechanical waves have minor effect on wells at distances more than 1000 m from the source.

4. The wellbore loss consumes about 70% of the original wave strength and this percentage depends on wellbore fluid type. Denser wellbore fluids allow more of the wave to penetrate the reservoir.

5. The wave frequency dictates both penetration radius and profile. Frequencies higher than 1000 Hz limit the wave penetration radius to a few meters into the reservoir.

NOMENCLATURE

Symbol	Definition	Unit		Symbol	Definition	Unit
A	The contact surface area	m^2		r	The distance from the wave source	m
B	Fluid formation volume factor	bbl/STB		r_e	Well drainage radius	ft
$B(r)$	The normalized correlation function	Dimensionless		r_w	Wellbore radius	ft
c	The fluid heat capacity	J/Kg.°C		s	Skin factor	Dimensionless
d	The rock layer thickness	m		S_{or}	Residual oil saturation	%, Dimensionless
h	Formation thickness	ft		T	The crude oil temperature	°C
h_c	The convective heat transfer coefficient	J/m².°C		V	The wave velocity	m/s
k	Absolute permeability	md		V_0	The constant background P-wave velocity	m/s
$K_d\ K_f$	The dry and fluid bulk modulus respectively	Pa		Z	The impedance	Kg/m².s
K_{Psr}	The wave number of Biot's slow wave	Dimensionless		**Greek**	**Definition**	**Unit**
k_0	The background permeability	md		α	The Biot–Willis coefficient	Dimensionless
m	The fluid mass	Kg		$\bar{\alpha}$	The attenuation coefficient	dB/m
p	Volumetric average reservoir pressure	psi		λ	The wavelength	m
P_{1m}	The wave power at a distance one meter from the source	watts		Δ_1, Δ_2	Special coefficients	Dimensionless
p_{1m}	The wave pressure at a distance one meter from the source	psi		μ	Fluid viscosity	cp
p_c	Capillary pressure	psi		μ_o	Oil viscosity	cp
P_d	The dry background P-wave modulus	Dimensionless		Λ	The rock thermal conductivity	W/m. °C
p_e	Average reservoir pressure	psi		ϕ	The background porosity	%, Dimensionless
p_{wave}	Wave pressure	psi		τ	The transmission coefficient	%, Dimensionless
p_{wf}	Bottom hole flowing pressure	psi		ω	The wave angular frequency	Hz
Q^{-1}	Wave Quality Factor	Dimensionless		ρ	The saturated bulk density	Kg/m³
q	Flow rate	bbl/day				

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