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Real-time Completion Monitoring with Acoustic Waves

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SUMMARY

Deepwater production is challenged by well underperformance issues that are hard to diagnose early on and expensive to deal with later. Problems are amplified by reliance on few complex wells with sand control media. New downhole data is required for better understanding and prevention of completion and formation damage. We introduce Real-Time Completion Monitoring, new non-intrusive surveillance method for identifying impairment in sand-screened completions that utilizes acoustic signals sent via the fluid column. These signals are carried by tube waves that move borehole fluid back and forth radially across the completion layers. Such tube waves are capable of "instant" testing of presence or absence of fluid communication across the completion and are sensitive to changes occurring in sand screens, gravel sand, perforations, and reservoir. The part of completion that has different impairment from its neighbors will carry tube waves with modified signatures (velocity, attenuation) and also would produce reflection from the boundary where impairment changes. The method would rely on permanent acoustic sensors performing acoustic soundings at the start of production and then repeating these measurements during the life of well. Thus, it could be thought of as "miniaturized" 4D seismic and "permanent log" in individual wellbore.

Motivation

Deepwater production increasingly relies on a few precious wells that are complex and expensive. Success is critically dependent on our ability to understand and manage these wells particularly at the sandface. These wells are filled with expensive “jewelry” like sand control and production allocation systems that aim at maximizing production and minimizing risk. While this smart equipment can mitigate many anticipated dangers, it can easily fail when something less expected happens. For example, repairing a sand control system failed due to plugging can cost US$30-40 million. Costs of lost production due to long-term well impairment can be much higher. Lower than expected production is often referred to as “well underperformance” and can be caused by various impairments: a plugged sand screen, contaminated gravel sand, clogged perforations, damaged formation around the wellbore or larger-scale compartmentalization. While 4D seismic can address large-scale compartmentalization, it has no resolution to address near-well issues. Scarce downhole data from pressure and temperature gauges also cannot unambiguously characterize the impairment. This limits mitigation opportunities and prevents us from finding more effective drawdown strategies for high-rate high-ultimate-recovery deepwater wells. We strongly believe that geophysical surveillance in boreholes has a big role to play in identifying sources of well impairment and optimizing production. Here we describe one possible avenue - real-time completion monitoring (RTCM) – that utilizes acoustic signals in the fluid column to monitor changes in permeability along the completion. In essence, this is a miniaturized 4D seismic in a well. We illustrate capabilities of acoustic surveillance through a series of full-scale laboratory tests with a realistic completion.

Basic concept of evaluating permeability with acoustic waves

At low frequencies acoustic signals in a fluid-filled borehole are mainly carried by tube or Stoneley waves. Inside the fluid column the tube wave mainly consists of a piston-like motion. When fluid is compressed, it attempts to expand radially and pushes against the formation or casing. When the borehole wall is permeable, then the tube wave can move the fluid through and this leads to a slowdown in velocity and an increase in attenuation (Tang and Cheng, 2004). Currently these principles are employed in estimating near-wellbore permeability from an open-hole acoustic logging (Tang and Cheng, 2004). Conceptually similar principles may be extended to deepwater production wells with sand-screen completions. These wells contain multiple permeable layers (sand screen, gravel sand, perforated casing, formation) as shown in Figure 1a. In unimpaired wells fluid can freely flow from the reservoir through all of these layers inside the borehole. However reduction of permeability in any of these layers (impairment) may greatly reduce the fluid flow. Low-frequency tube waves can conduct instant pressure testing and therefore indicate whether fluid communication is blocked, thus providing valuable information about impairment location and strength. While this sounds conceptually similar to the open-hole case, the quantitative interpretation is different because wells with sand screens (or additional inner pipe) support two tube waves and their permeability dependence is more complicated.

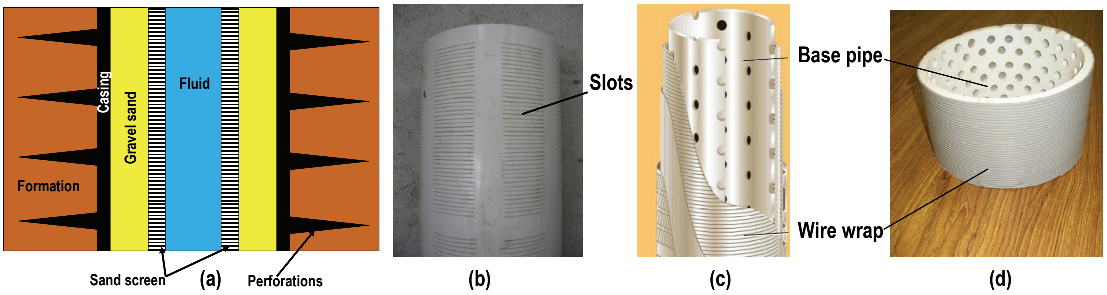

Figure 1: (a) Schematic cross-section of a sand-screened completion in a cased borehole; b) slotted PVC screen used in the current experiments; c) a premium sand screen, named as Excluder (www.bakerhughesdirect.com); d) wire-wrapped PVC sand screen.

Laboratory setup with a horizontal well

Figure 2 depicts the schematics and photograph of a horizontal flowloop setup used for the experimental measurements. The outer pipe (casing) with length of ~ 30 ft (9 m) consists of six 5-ft sections joined together and attached to the underlying support rail. The inner pipe (sand screen) is positioned inside using plastic centralizers. The inside as well annulus between the inner and the outer pipe are filled with water. Measurements are conducted with 24 hydrophones spaced at 35 cm and a piezoelectric source.

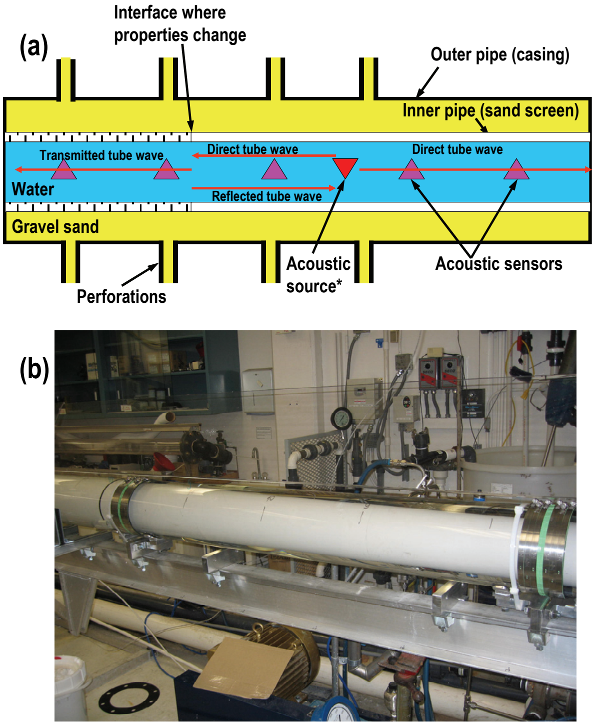

Figure 2: (a) Sketch of the flowloop setup with the model of sand-screened completion in horizontal well. (b) Photograph of the actual flowloop setup at Shell's Bellaire Technology Center with a glass outer pipe (no perforations).

Completion without gravel pack: experiment vs. modeling

As shown by Bakulin et al (2008) wave propagation in such model supports four symmetric modes: two tube waves and two plate waves. First tube wave is supported by inner fluid column. Likewise, second tube wave is supported by the outer fluid column. Two plate or extensional waves, supported by two pipes, are small and not considered here. In this study we focus to analyze the effect of sand screen plugging on the transmission signatures of the two tube waves. To model a permeable sand screen or "open pores" we used a slotted screen (Figure 1b). Other configurations of sand screens are shown on Figure 1c-d. To model a completely plugged screen or "closed pores" we used a PVC pipe without slots.

Figure 3(left) shows the raw acoustic wavefield recorded in the case of no screen and a screen with "open" or "closed" pores. The acoustic data is contaminated by reflections from pipe joints. Nevertheless the first conclusion is immediate: in the absence of a screen, there is only one (fast) tube wave present with velocity of about 1050 m/s. When an impermeable inner pipe is added (closed pores) a slow tube wave appears, and the fast tube wave becomes more attenuative due to high absorption in PVC screen. When the inner pipe becomes slotted (open pores) then fluid on both sides of the PVC screen start to communicate, and this leads to a very strong attenuation of both tube waves. Thus a greatly increased attenuation of both fast and slow tube waves is the first-order diagnostic for open screens ("open pores"), whereas reduced attenuation is characteristic for plugged screens ("closed pores"). Thus if plugging develops we start to see a big signal.

Additional diagnostics can be established by analyzing energy distribution as a function of frequency between these two cases. This analysis is best performed using the slowness-frequency spectra shown in Figure 3(middle). Figure 3(right/top) represents the averaged velocity spectrum over the entire frequency range which is the horizontal stack of Figure 3(middle). Both fast and slow tube waves with approximately the same velocities of 1100 m/s and 350 m/s are present in the plugged and open cases, however the slow wave is completely absent without a screen. In a plugged screen the fast wave carries maximum energy in the frequency range of 300-600 Hz close to the dominant frequency of the source, whereas lower and higher frequencies carry less energy [Figure 3(middle)]. In contrast, the spectrum of the fast wave in an open screen has a big energy "hole" between 300 and 600 Hz where the fast wave is attenuated so strongly that even higher frequencies (600-900 Hz) carry more energy [Figure 3(middle)]. This behavior is summarized in Figure 3(right/bottom), which confirms that fast-wave energy is severely attenuated in the medium frequency range whereas it is still preserved in the high-frequency range. As for the slow tube wave, it mainly exists at frequencies below 600 Hz and is also attenuated.

Let us compare this behavior with the poroelastic reflectivity modeling. Figure 4(left) shows synthetic seismograms computed for a glass setup with our best guess of poroelastic parameters for the screen (130 Darcy). Similar to the experiment, in the case of closed pores we observe two tube waves with the fast tube wave dominating in amplitude. In the presence of a screen with open slots both waves experience strong changes. The fast tube wave experiences moderate attenuation and change of waveform. The slow tube wave transforms into a complex packet with weak amplitude.

The following physical interpretation can be given to the modeled results. A tube wave is born when the piston-like motion of the fluid inside the pipe creates a radial expansion that is resisted by the elastic pipe. The slow wave is supported mainly by the inner pipe. When this pipe becomes slotted, radial movement of the fluid is no longer resisted since liquid can freely escape to the annulus, thus leading to a strong attenuation of this wave. In contrast, the fast wave is supported mainly by the outer glass solid pipe. When the inner pipe becomes permeable, piston-like motion of the fluid in the fast wave can additionally exchange the fluid between the outer and the inner fluid columns, thus creating a moderate attenuation.

Slowness-frequency spectra for open pores [Figure 4(middle)] shows, that, similar to the experimental results the fast wave experiences anomalously high attenuation in the medium frequency range of 350-700 Hz. In addition, velocity slows down at low frequencies and the energy peak becomes broader, indicating dispersion. A more robust display averaging over "small", "medium" and "high" frequencies is shown on Figure 4(right). Comparison of Figure 4(right) and Figure 3(right) confirms the qualitative agreement between experiment and modeling: in both cases the fast wave exhibits anomalous amplitude decrease in the medium frequency range, while still preserving higher and lower frequencies. The frequency range with resonance attenuation is controlled by permeability - when permeability decreases from 130 to 50 Darcy then this band moves from 350-700 Hz to 600-1000 Hz, i.e. the lower the permeability, the higher the frequency of the band with anomalous attenuation of the fast wave. Therefore central frequency of the band with anomalous attenuation of the fast tube wave is an additional useful diagnostic of the screen permeability.

Conclusions

We propose a new technique that monitors changes in permeability along sand-screened completions utilizing acoustic signals in the fluid column. Various impairment mechanisms can impede production in real wells. We presented a full-scale laboratory test verifying the method for a scenario where impairment is caused by sand-screen plugging in a completion without a gravel pack. We observe two tube waves supported by the screen and casing, with the slow tube wave being a diagnostic of a completion without a gravel pack. Simple inspection of the raw data allows identification of plugged and open sections of the screen: plugged sections give large signal, whereas open sections have low signal (greatly increased attenuation of both fast and slow tube waves). If permanent acoustic sensors are deployed across the sandface, then experimental monitoring of the tube-wave signatures over time can reveal plugging of the sand screen or its parts. Bakulin et al (2008) described a fiber-optic "on the pipe" acoustic system suitable for permanent installation that can allow non-intrusive real-time completion monitoring. Similarly repeated production logging with (non-permanent) acoustic tools can quantify completion impairment but not in real time.

We further compared experimental results with simple poroelastic modeling and found a qualitative agreement between most of the experimentally measured and predicted signatures.

References

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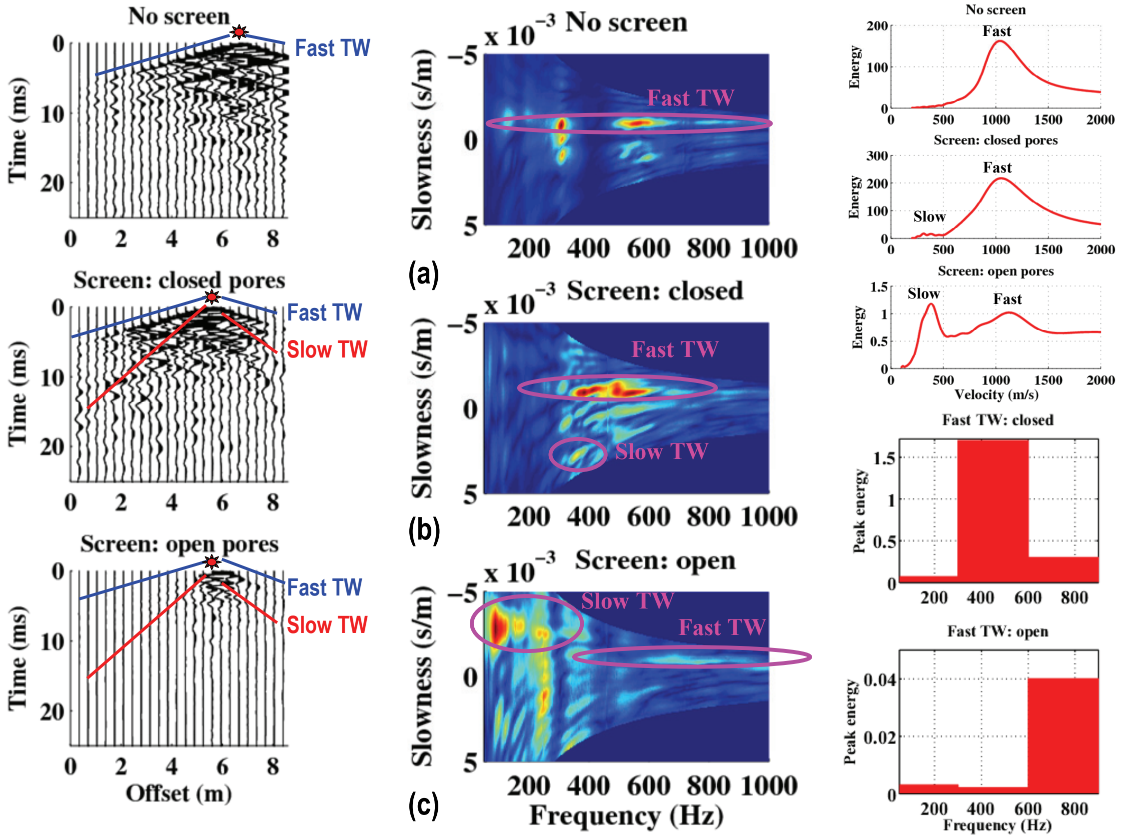

Figure 3: *Left:* experimental seismograms recorded in the laboratory test. *Middle:* slowness-frequency displays of the experimental data: note that without sand screen we only have fast tube wave (a). With plugged sand screen slow tube wave appears (b), whereas permeable sand screen attenuates both tube waves to a great degree (c). *Right:* velocity spectra (stack of middle figures) [top]. Energy distribution vs. frequency for the fast tube waves in open and plugged screens (bottom). Note anomalous attenuation between 300 and 600 Hz

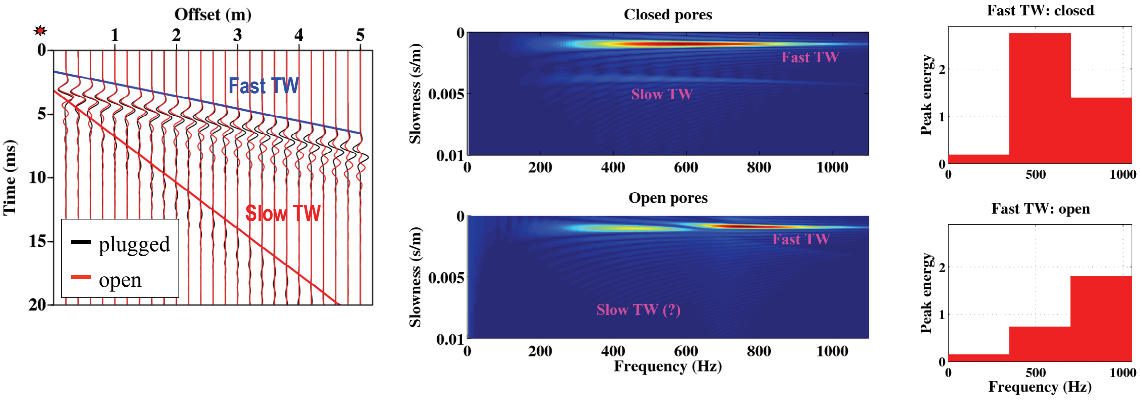

Figure 4: *Left:* synthetic data for laboratory setup with open and plugged screens (left). Note larger attenuation and dispersion of fast tube wave in open screens. *Middle:* slowness-frequency display of synthetic data. Note “anomalous” attenuation of the fast wave between 350 and 700 Hz similar to Figure 3(middle) of experiment. *Right:* energy distribution vs. frequency for the fast wave as predicted by numerical modeling. Note “anomalous” attenuation of the fast wave between 350 and 700 Hz similar to Figure 3(right/bottom) of experiment.