Author comments to the reviewers:

Potsdam (Germany), the 20th of September 2021

Dear Mr. Ryan Schultz,

Thank you for your time and effort in reviewing our publication. Your input and suggestions are valuable to us. Below, you find our replies (in grey) to your comments (in black).

Best regards,

Martin Lipus

Reviewer 1:

Review of Solid Earth article MS# 2021-63,

The manuscript of Lipus et al., "Dynamic motion monitoring of a 3.6 km long steel rod in a borehole during cold-water injection with distributed fiber-optic sensing" is an article concerning the observation of thermally induced stick-slip events. Cold water pumped into a well causes the rod inserted into the well to contract, with shaking from the stick-slip events recorded on DAS. The results are compared against DAS and DTS data to build a picture of where and why these events are occurring in the well. I think that the results of the paper could be interesting the readership of Solid Earth.

For this paper, I have only a few small critiques that should be addressed before acceptance with Solid Earth. In general, my comments revolve around better explaining some of the arguments the authors are trying to make. A more detailed list of my thoughts follows below:

In the conclusion, the acronym FO is used for the first time. I'm assuming it means fibre optic. I'd recommend removing it, as it's only ever listed here.

Acknowledged. Thank you.

From the results of this paper, it should be possible to get a rough estimate of what the coefficient of friction is between the well and the rod. Would be interesting to get a back-of-the-envelope sense of what that value is.

The presence of the first events coincides with the temperature, the theoretical model predicts its occurrence. Therefore, the literature values assumed for the static friction between sucker rod and steel liner are assumed to approximate the real values. A note was added to the discussion:

Was:

"In other words, the thermal stresses on the rod construction in this depth region are high enough that the rod starts to move and to contract."

Now reads:

"In other words, the thermal stresses on the rod construction in this depth region are high enough that the rod starts to move and to contract. Hence, the literature values assumed for the static friction between sucker rod and steel liner are assumed to approximate the real values."

In Section 4.1 the authors talk a bit about errors that apply in the measured and expected strains. I'm curious as to what sorts of errors could be introduced from the DAS data based on the response spectrum of the fibre optic cable. Are we potentially attenuating frequencies that could contribute significantly to the measured strain?

In the upper part of the well, the calculated strain derived from the DAS data shows variations related to the temperature change measured from the optical fiber. The change in strain is visible as an offset from zero in the strain rate data. In the reservoir section of the well, the strain development coincides with the stick-slip events. In the deepest part of the well, no temperature change and no strain change were observed; no offset from zero was measured in the strain rate data due to the temperature change. This led to the following conclusions:

Assuming that any vibration would lead to a variation of strain rate data around zero (+offset due to temperature changes), possible attenuation phenomena for specific frequency bands related to the installation design should not contribute to the overall strain change. Only if very low frequencies (<<1Hz, similar or lower than the temperature changes) were attenuated, this could have an effect. We find it unlikely that such low frequencies can occur.

To verify that there are no drift phenomena of the measurement system influencing the result, we analyzed the lower part of the cable where no temperature change was observed. Here, we also did not find any strain change.

As the system acquired data at 10kHz and downsampled it to 1kHz, higher frequencies might be visible as a beat frequency (that might be interpreted as a very low frequency signal). We do not expect a significant contribution at such high frequency.

The following page lists minor corrections and typos to be fixed.

Thanks,

-Ryan

Near Lines 372 & 377 & elsewhere: "extend" should be "extent"

Acknowledged. Thanks!

Figure 9: Why do events only seem to occur at the top of the casing liner after ~16 minutes?

We can name five effects that might contribute to the question why the events occur in particular at the top of the casing liner. Firstly, along the entire well path, the cooling from fluid injection is highest in this depth interval close to the top of the liner, where the most prominent geological feed zone lies. Consequently, the calculated force from thermal contraction is highest here (orange graph in Figure 10). Below that depth, the thermal contraction steeply decreases. The cummulative static friction of the rod construction is lowest at the bottom of the well and increases towards the surface (black graph in Figure 10). Both orange and black graph happen to "meet" around ~16 minutes after injection start close the top of the liner zone. Therefore, many events occur in this depth - and at that particular time. Secondly, the static friction force of the rod gradually increases towards surface, meaning that it is less and less likely for any relative motion to occur at shallower depth. Thirdly, we see that the gyro recording shows a sudden increase in the inclination of the borehole at 2850 m MD (see third panel in figure 4) and consequently an increase in F_N due to the higher angle. Effect No. 4 is that there is a change in diameter at the liner hanger. Effect no. 5: Above the top if the casing liner, fluid moves along the rod resulting in motion of the rod and hence sliding friction. Below, there is only static friction left that must be overcome first before shallower sections of the rod can move.

Section 2 rework:

2. Data Analysis

The analysis in this study is based on the comparison of strain derived from fiber-optic distributed temperature sensing (DTS) on the one hand and distributed acoustic sensing (DAS) on the other.

2.1 Derivation of strain from ~~Distributed Temperature Sensing~~DTS

DTS uses each location of a glass fiber as a sensor for temperature (*Hartog, 1983, Hartog and Gamble, 1991*). This is achieved by coupling laser-light pulses into a glass fiber and analyzing the Raman spectrum of the backscattered light whose origin along the fiber is determined by the two-way travel time of the light. In this study, we use a system based on Raman backscatter. Temperature profiles were acquired every 10 minutes with a spatial sampling of 0.25 m. Detailed information about the performance of the fiber-optic system and the calibration procedure are presented in *Schölderle et al., 2021*.

We calculate the change in temperature from DTS at the start of fluid injection and the profile later during fluid injection. ~~From the temperature change ΔT, a theoretical thermal contraction of the rod is calculated by multiplying ΔT with the thermal expansion coefficient α_{rod} of the rod. We compare this theoretical thermal contraction with strain information inferred from DAS measurements along the rod. We then use the DTS data to compute stresses along the rod which occur due to cooling.~~

~~2.3 Deformation balance from DTS and DAS measurements~~

From DTS measurements we may predict ~~themo~~thermo-mechanical deformation according to

$$\varepsilon_{DTS}(x) = \alpha_{rod} \cdot \Delta T(x) \qquad (1)$$

where α_{rod} is the thermal expansion coefficient and $\Delta T(x)$ is the temperature difference at two subsequent points in time at some location x of the fiber. The rod construction as a whole consists of many different materials with different thermal expansion coefficients, such as the sensing fibers, gel filling, metal tubes, polypropylene mantle, steel rod and nylon centralizers. However, the steel of the sucker rod and the steel of the fiber-optic mantle are the dominant material by weight and the most relevant for any thermal stresses. The sucker rod consists of 4332 SRX Nickel Chromium Molybdenum steel with a thermal expansion coefficient of 10 - 13 µϵ/K (*Hidnert, 1931*) and a modulus of elasticity of 200 GPa (*T.E. Toolbox, 2012*). The second most dominant material is the polypropylene cable mantle with a modulus of elasticity of 1.5-2 GPa (*T.E. Toolbox, 2012*). The proportion of steel on the thermal stresses in the rod construction are 99.8%. For simplicity, we assume that thermal expansion coefficient α_{rod} = 13 µϵ/K for the sucker rod / fiber-optic cable construction and neglect the other materials. ~~In our study, DAS data is acquired at 10000 Hz and down-sampled to 1000 Hz~~

2.2 Direct measurement of strain via DAS

Similar to DTS, DAS also analyzes the back scatter of light coupled into a fiber from one end. Upon contraction or dilatation, the strain-rate of the fiber, i.e. the temporal derivative of relative change of length, can be derived from the temporal change of the interference pattern of coherent light elastically scattered (Rayleigh scattering) from adjacent points within a certain interval of fiber called the gauge length (*Masoudi et al., 2013)*. The centroid of the gauge length is defined as a sensor node. The location (x) of a sensor node along the fiber is again determined by the two-way travel time of light from its source to the node and back. In our study, DAS data is acquired at 10000 Hz and down-sampled to 1000 Hz. The gauge length and spatial samping are 10 m and 1 m, respectively. No additional filtering was applied in post-processing (no high pass and no low pass filtering).

In contrast to DTS, DAS directly yields the temporal derivative of strain. In order to convert the measured strain rate $\dot{\varepsilon}$(x,t) data to strain $\varepsilon_{DAS}(x)$ at each location, we integrate in time:

$$\varepsilon_{DAS}(x) = \int_{t1}^{t2} \dot{\varepsilon}(x,t)dt \qquad (2)$$

where t1 and t2 delineate the time window and $\dot{\varepsilon}$(x,t) the recorded strain rate at position x. In the following we speak of “measured strain” ε_{DAS} in contrast to “predicted or expected” strain ε_{DTS}.

We compare ε_{DTS} with ε_{DAS} measurements. We then use the ε_{DTS} data to compute the contractional forces along the rod which occur due to cooling. We compare the result with a static friction curve that was estimated from the sucker rod tally and borehole inclination.