

# Physics-based model relating seismic velocity variation to groundwater and pore pressure fluctuation



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## Introduction

Monitoring studies<sup>[1;2;3;4;5]</sup> of the groundwater table and the pore pressure rely on empirical relationships with the seismic velocity, lacking a physical basis. Here we provide such a physics-based relationship for seismic velocity change, induced by changes in pore pressure and vertical compressional stress. To this end, we combine the from first principles derived relationship between induced stress and velocity change<sup>[6]</sup> with basic hydrology, geomechanics and wave propagation theory. Using data collected in Groningen, the Netherlands, we validate this relationship and show that changes in the pore pressure can be monitored using passive seismic interferometry.

## Theory

### Induced effective stress

$$\mathbf{T}'^0 = \mathbf{T}^0 + u^0 \mathbf{I} = \begin{pmatrix} u^0 & 0 & 0 \\ 0 & u^0 & 0 \\ 0 & 0 & u^0 + T_{33}^0 \end{pmatrix}$$

Horizontal propagation, horizontal motion:

$$\left(\frac{d\beta}{\beta}\right)_{SH}^{Hor} = -\frac{\mu'}{2\mu} u^0,$$

### Shear wave velocity change<sup>[6]</sup>

Vertical propagation, horizontal motion:

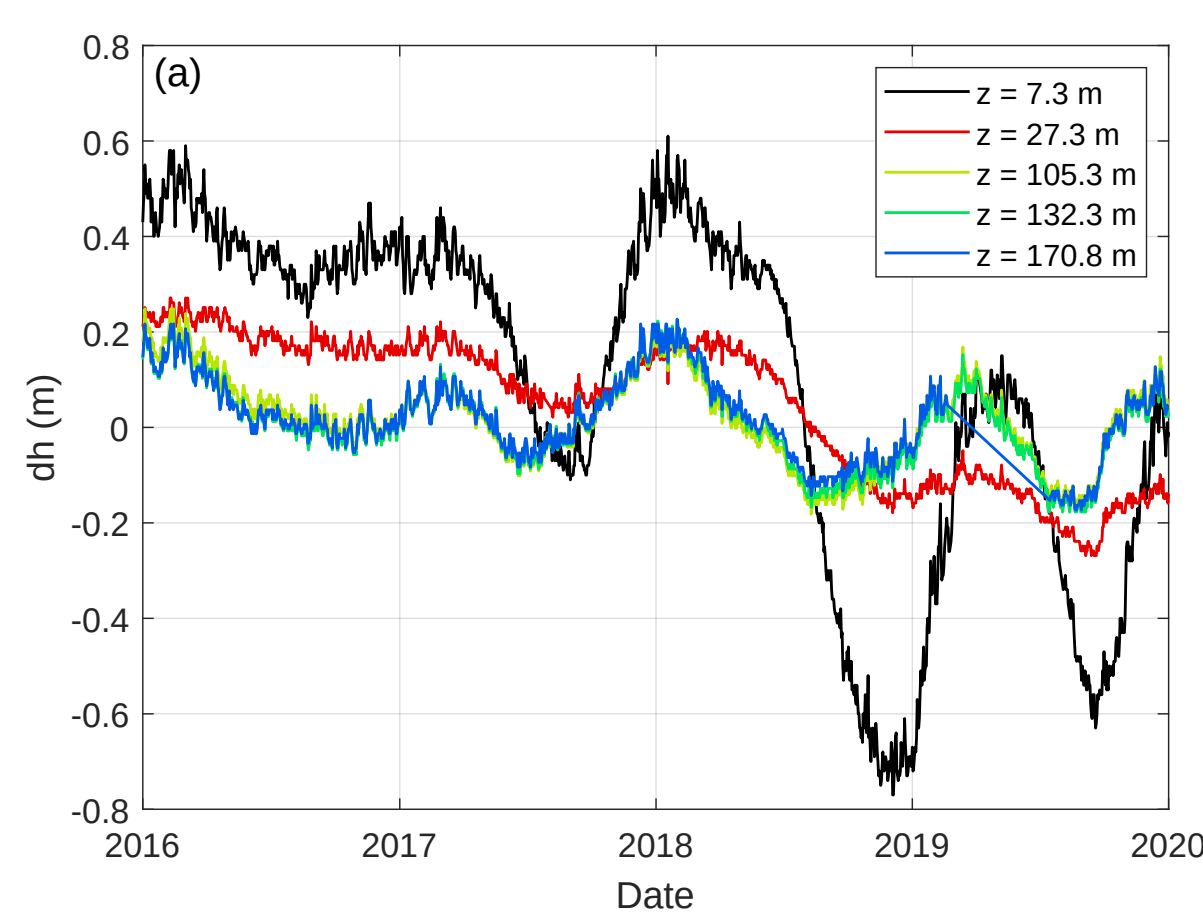
$$\left(\frac{d\beta}{\beta}\right)^{Vert} = -\frac{\mu'}{2\mu} u^0 - \frac{\mu' - 1}{4\mu} T_{33}^0,$$

Horizontal propagation, vertical motion:

$$\left(\frac{d\beta}{\beta}\right)_{SV}^{Hor} = -\frac{\mu'}{2\mu} u^0 - \frac{\mu' + 1}{4\mu} T_{33}^0.$$

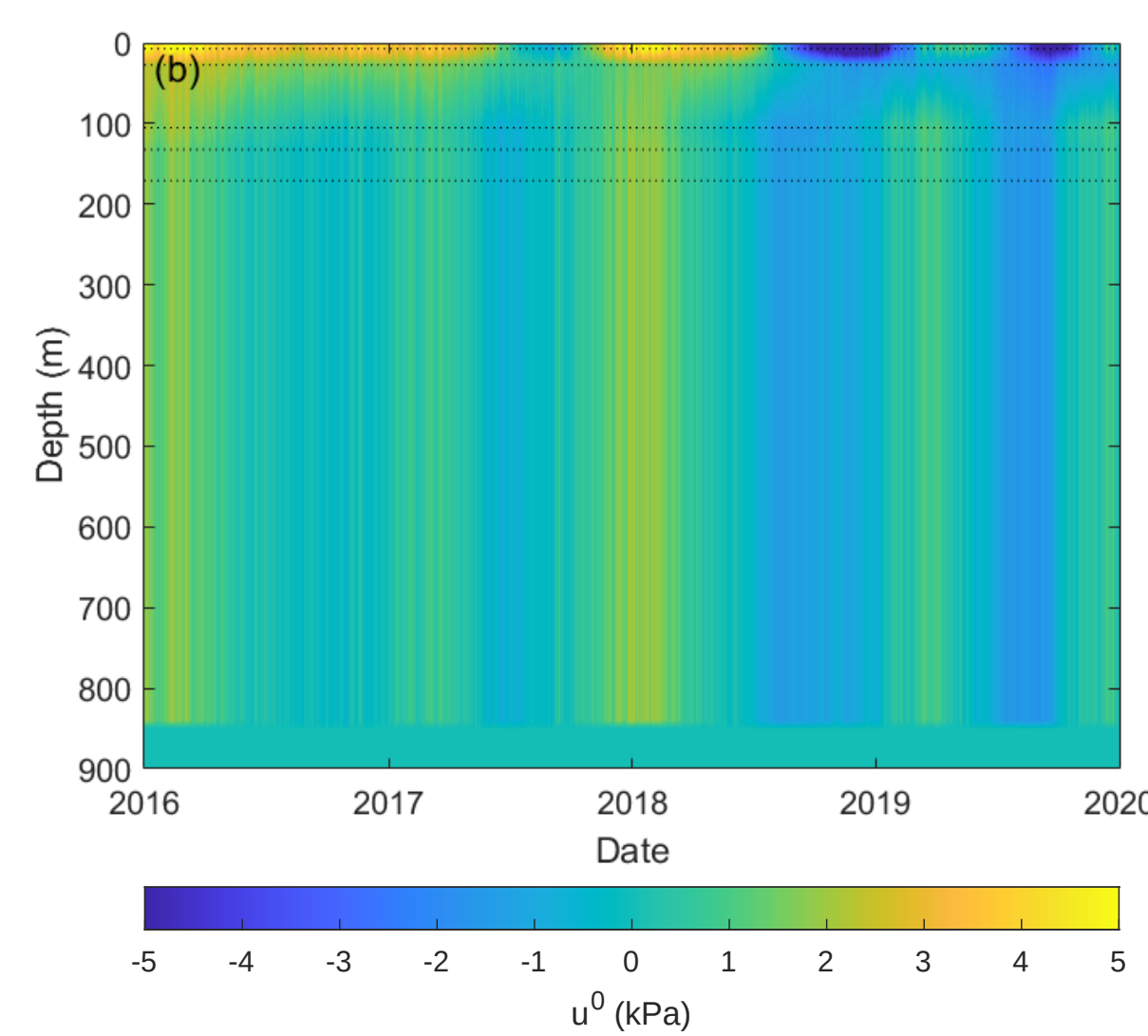
## Validation

### Hydraulic head measurement



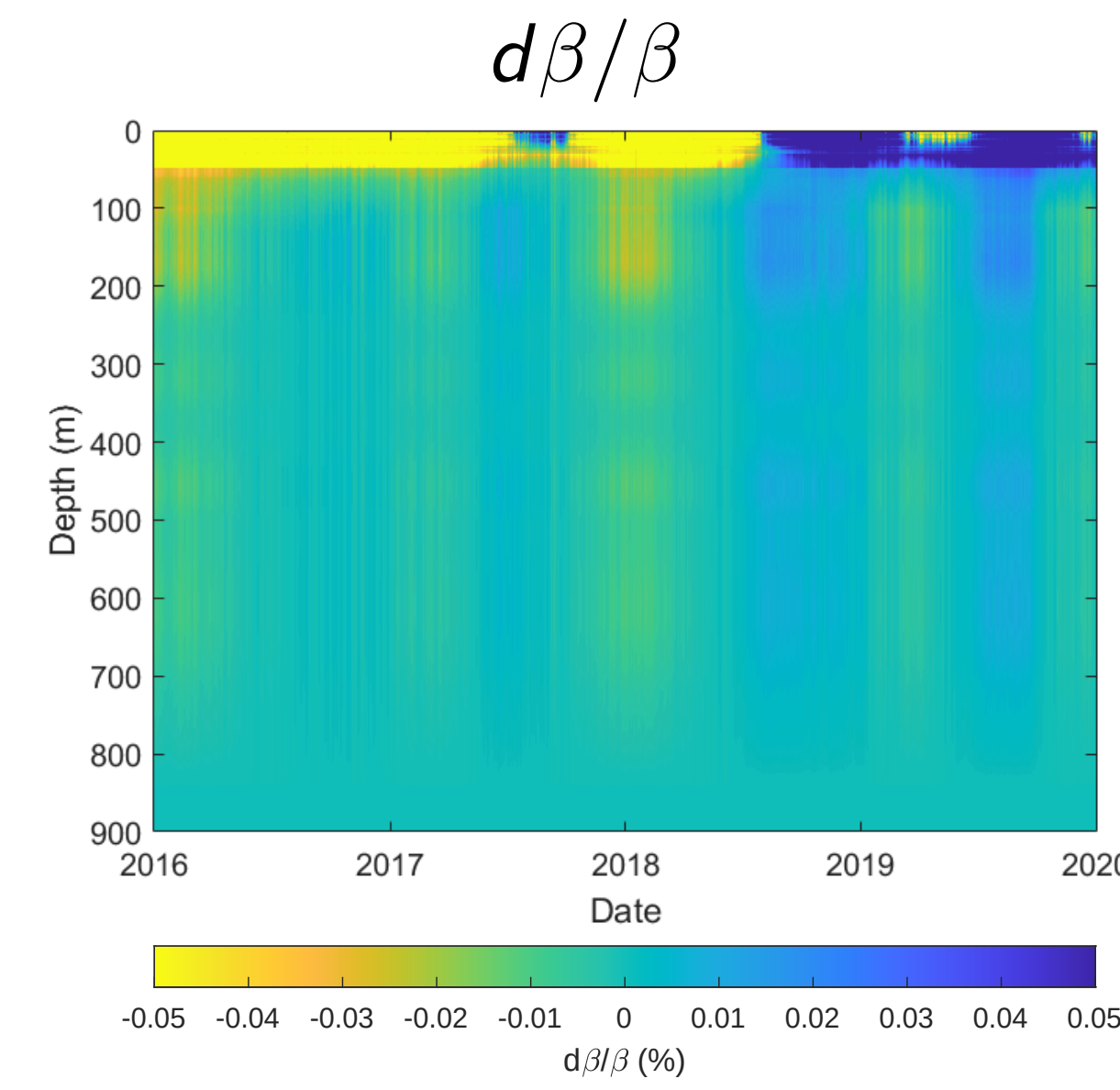
Change in hydraulic head  $dh$  with respect to average between 01 Jan 2017 and 01 Jan 2020

### Change in pore pressure $u^0$



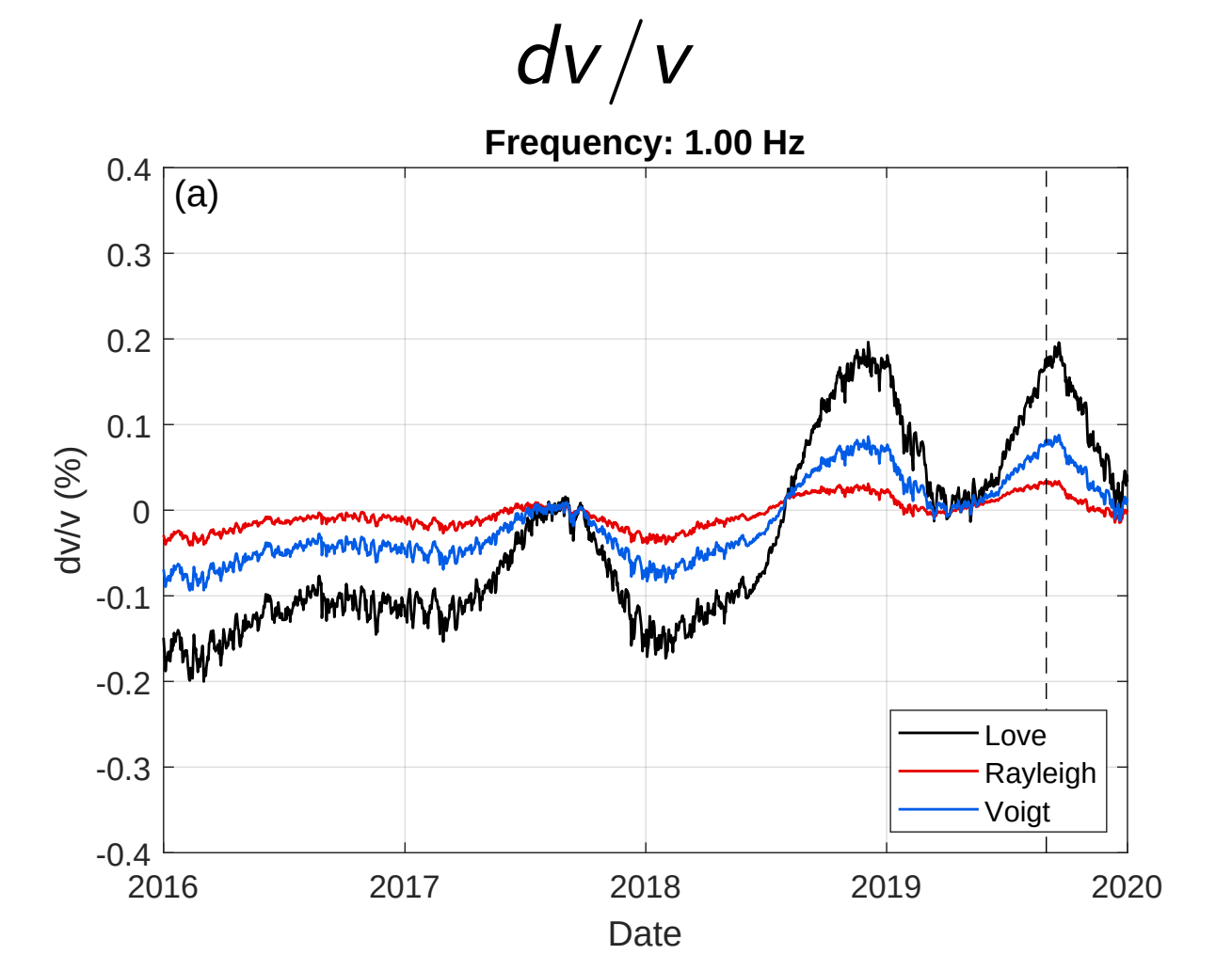
Pore pressure obtained from hydraulic head  $u^0 = \rho g dh$

### Shear-wave velocity change



Model for shear-wave velocity change  $\frac{d\beta}{\beta} \approx -\frac{\mu'}{2\mu} u^0$

### Surface-wave velocity change



Surface-wave velocity change modelled using the adjoint technique<sup>[7]</sup>

### Passive seismic interferometry

To obtain seismic velocity changes we applied passive seismic interferometry, consisting of two processes. (1) The Green's function is estimated using the cross-coherence<sup>[8]</sup> between multiple combinations of seismic receivers. (2) Seismic velocity changes are obtained using the time-stretching method<sup>[9]</sup> on lapse and reference cross-coherences.

### Green's function estimation

Cross-coherence  $H$ <sup>[8]</sup>:

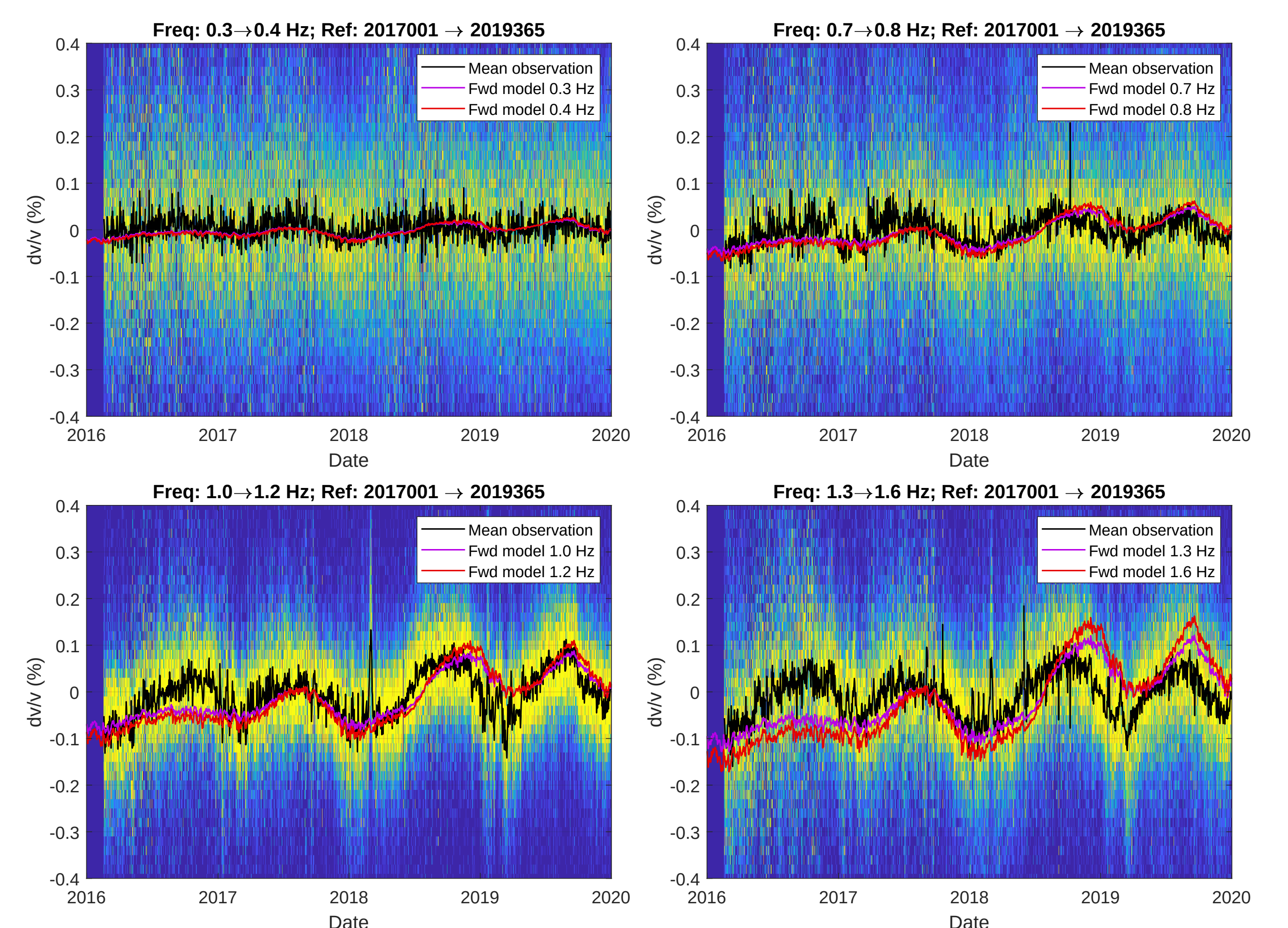
$$\hat{H}(x_B, x_A, \omega) = \frac{\hat{u}(x_A, \omega) \hat{u}^*(x_B, \omega)}{|\hat{u}(x_A, \omega)| |\hat{u}(x_B, \omega)|}$$

### Velocity change determination

Time-stretching correlation<sup>[9]</sup>:

$$CC(\epsilon) = \frac{\int_{t_1}^{t_2} H_{\text{lapse}}[t(1-\epsilon)] H_{\text{ref}}[t] dt}{\sqrt{\int_{t_1}^{t_2} (H_{\text{lapse}})^2 [t(1-\epsilon)] dt} \sqrt{\int_{t_1}^{t_2} (H_{\text{ref}})^2 [t] dt}}$$

### Surface-wave velocity change - Model and observation



## Conclusions

- Physics-based relationship for seismic velocity change induced by pore pressure and vertical stress
- Good match in shape and magnitude between model and observation
- First order validation using data collected in Groningen, the Netherlands
- Passive seismic interferometry proves suitable for pore pressure monitoring in Groningen, the Netherlands

## References

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