Estimating moisture changes in concrete using GPR velocity analysis: potential and limitations

supported by: Geo.X

Philipp Koyan*, Jens Tronicke, Niklas Allroggen
Institut für Erd- und Umweltwissenschaften
Universität Potsdam (Germany), *koyan@uni-potsdam.de

Andreas Kathage
GeoHiRes International GmbH
Borken (Germany)

Michael Willmes
Implenia Construction GmbH
Mannheim (Germany)

1. Motivation and introduction

Chloride-induced corrosion of steel rebars is a key problem for the durability and safety of reinforced concrete buildings such as bridges. Penetrating rainwater transports the chlorides into exposed parts of these buildings. Hence, the characterization of moisture conditions and their tempo-spatial variability is a fundamental part of an on-site practical investigation.

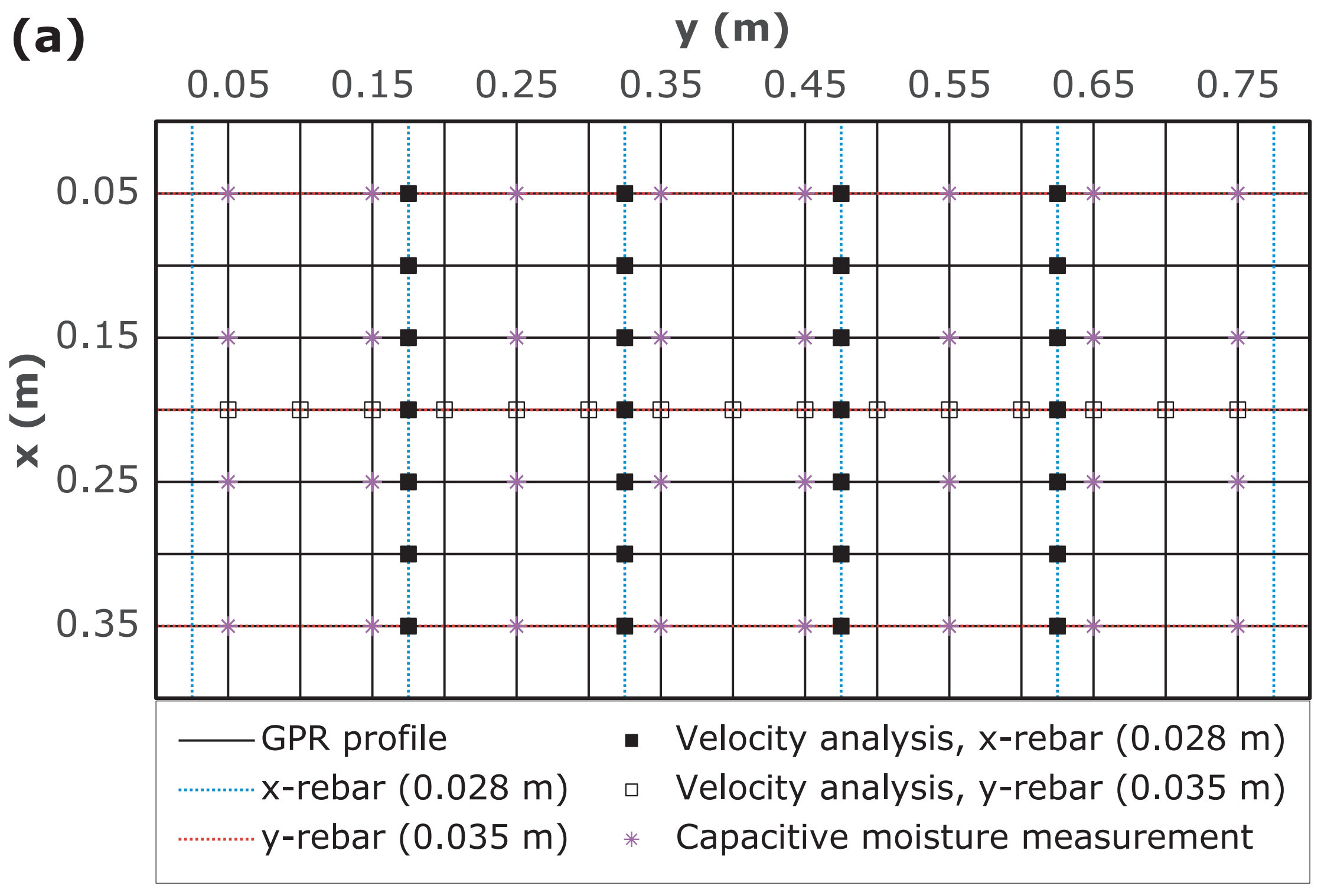
Ground-penetrating radar (GPR) is a common tool for efficient non-destructive imaging of small-scale structural defects in concrete. When evaluating constant-offset GPR data, the analysis of diffraction hyperbolas yields quantitative information on GPR velocity, and thereby on the water content of the medium. However, when performing a thorough velocity analysis to estimate moisture content, precise information on time zero is a key problem.

In this study, a GPR monitoring experiment has been performed under laboratory-like conditions across a reinforced concrete specimen. We show the results of a typical processing flow providing a highly-resolved structural image. Furthermore, we develop and apply a migration-based velocity and time-zero analysis and calculate changes in moisture content. We compare our results to independent measurements of concrete moisture to evaluate the potential and limitations of GPR for estimating tempo-spatial changes in concrete moisture content.

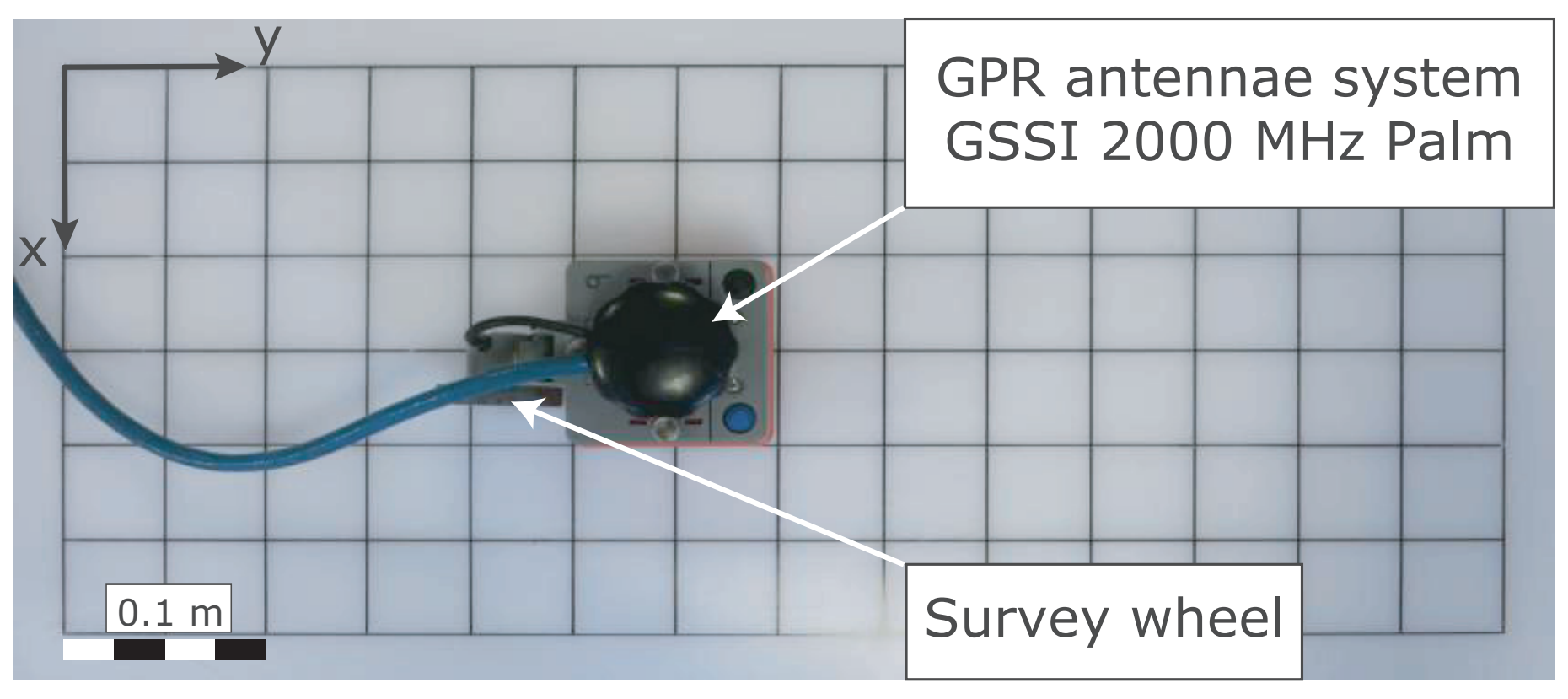
2. Experimental setup & data acquisition

- **(a)** Specimen shows rebar geometry (depths and spacings) typically employed in buildings such as bridges
- HDPE sheet with thickness of 0.03 m covered 0.1 m thick specimen during GPR data acquisition; i. a., to simulate a realistic two-layer case with a high-velocity layer (i. e., asphalt; v_1) covering concrete (v_2)
- **(b)** Acquisition of 2D constant-offset GPR data (2 GHz) before and after immersion of specimen in water
- For comparison, capacitive and gravimetric moisture measurements performed concurrently to GPR surveys

(a)

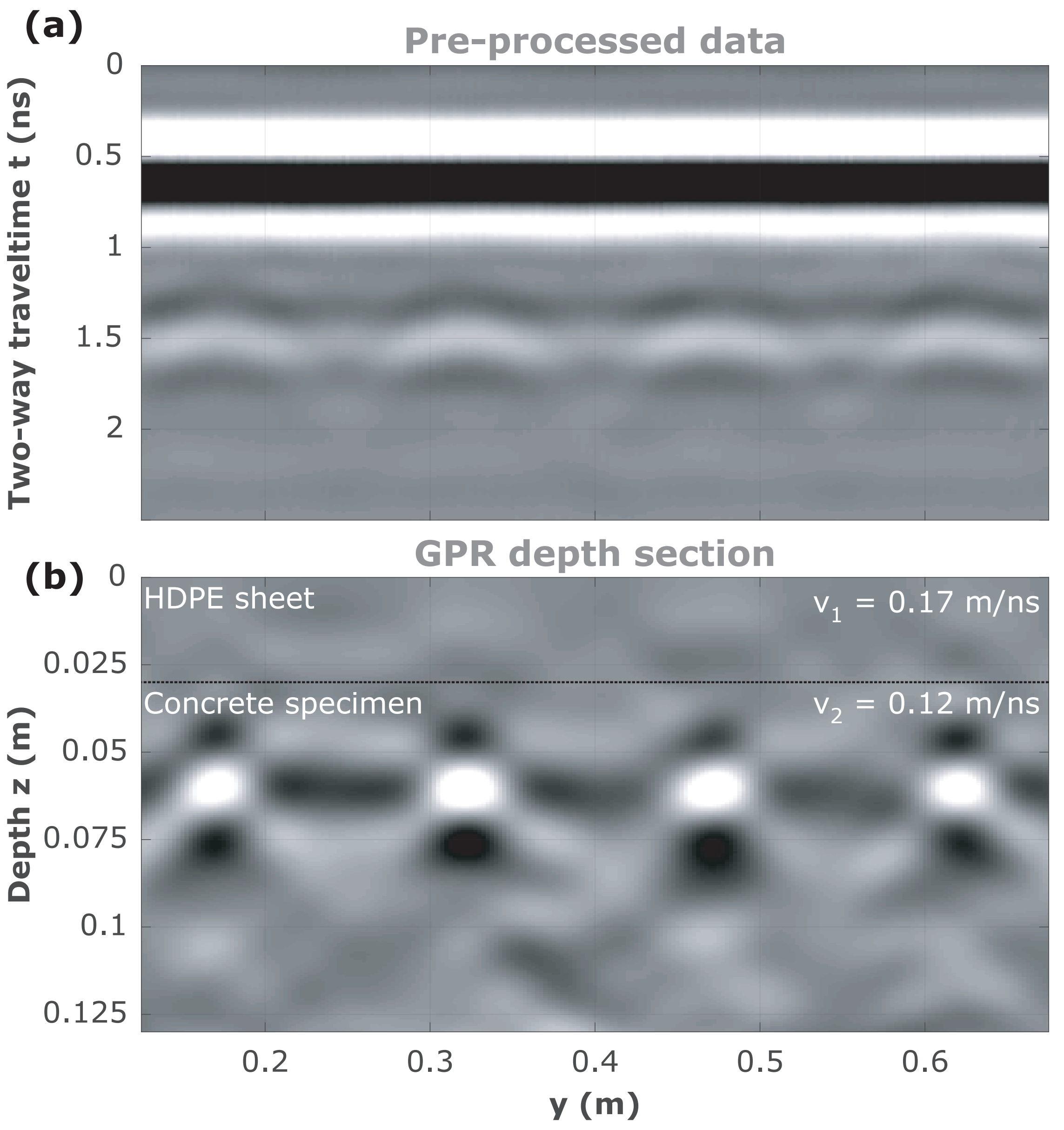


(b)



3. Structural imaging

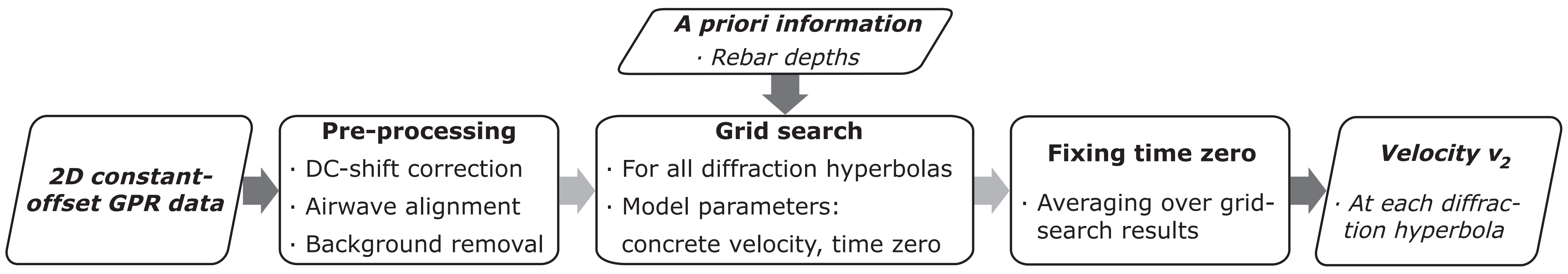
- **(a)** GPR profile recorded at x = 0.2 m across saturated specimen after pre-processing (including DC-shift correction and airwave alignment)
- Pre-processing result: Stable direct wavelet, clear diffraction hyperbolas
- **(b)** GPR depth section after band-pass filtering, spectral whitening, background removal, time-zero correction, amplitude scaling, 2D Kirchhoff migration
- Time zero estimated by maximum energy in direct wavelet, rms velocity by manual hyperbola fitting
- Processing result: Rebar locations precisely imaged



4. Estimation of concrete moisture changes

4.1 Migration-based velocity and time-zero analysis

- Grid-search-inversion routine to estimate concrete velocity v_2 and time zero t_0 as model parameters
- Non-unique inversion problem: A priori information necessary to constrain inversion results
- Analysis strategy developed using 28 diffraction hyperbolas (originating from x-rebars) recorded on saturated specimen



A priori information
· Rebar depths

2D constant-offset GPR data

Pre-processing
· DC-shift correction
· Airwave alignment
· Background removal

Grid search
· For all diffraction hyperbolas
· Model parameters: concrete velocity, time zero

Fixing time zero
· Averaging over grid-search results

Velocity v_2
· At each diffraction hyperbola

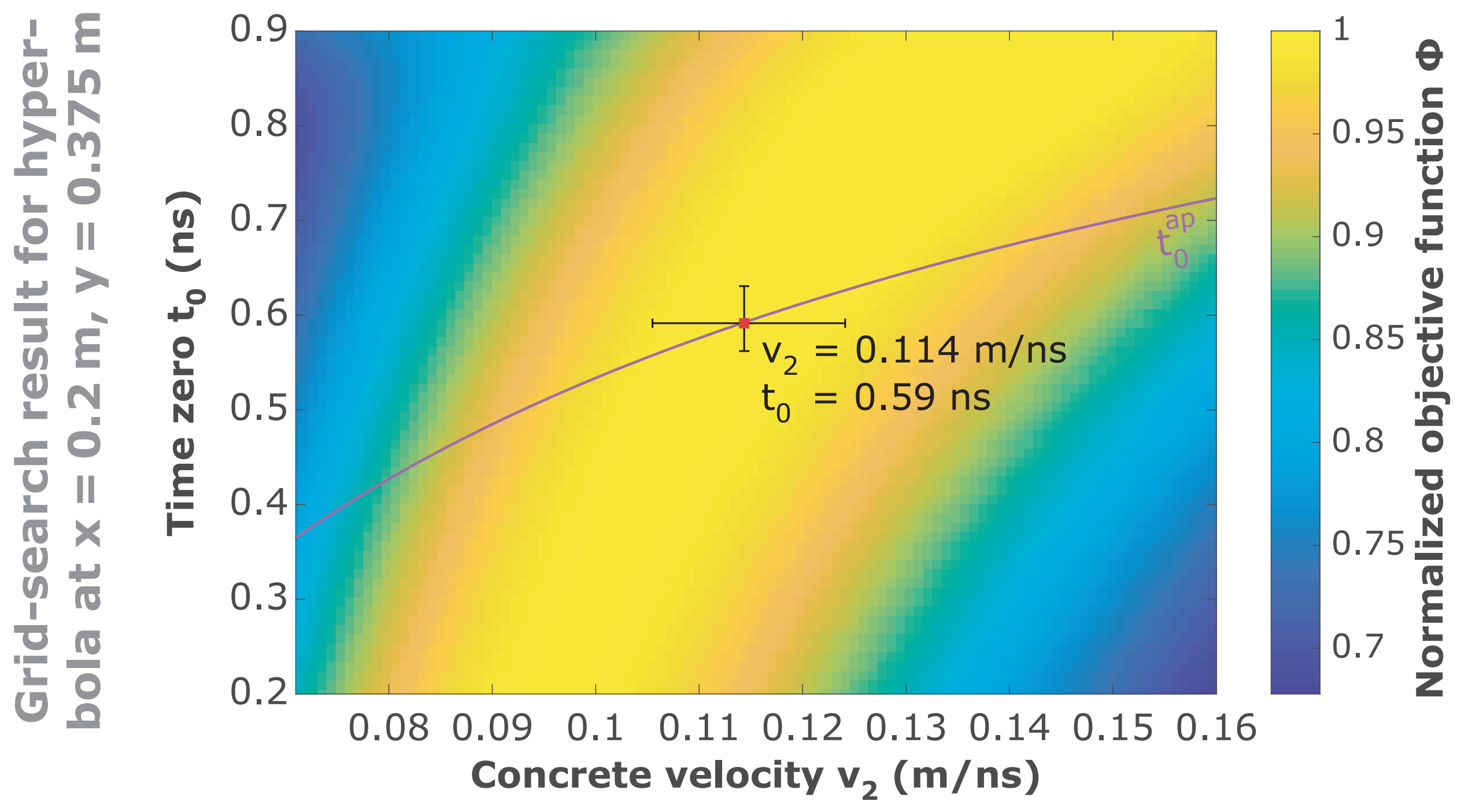
4.2 Methodology and application

- For every diffraction hyperbola and model parameter combination:
  (1) Apply time-zero correction and calculate rms-velocity model v_{rms} with v_1 = 0.17 m/ns and variable concrete velocity v_2
  (2) Perform diffraction summation using

$$t^2 = \tau^2 + \left(\frac{2(X_m - X_0)}{v_{rms}}\right)^2 + \left(\frac{X_{off}}{v_{rms}}\right)^2,$$

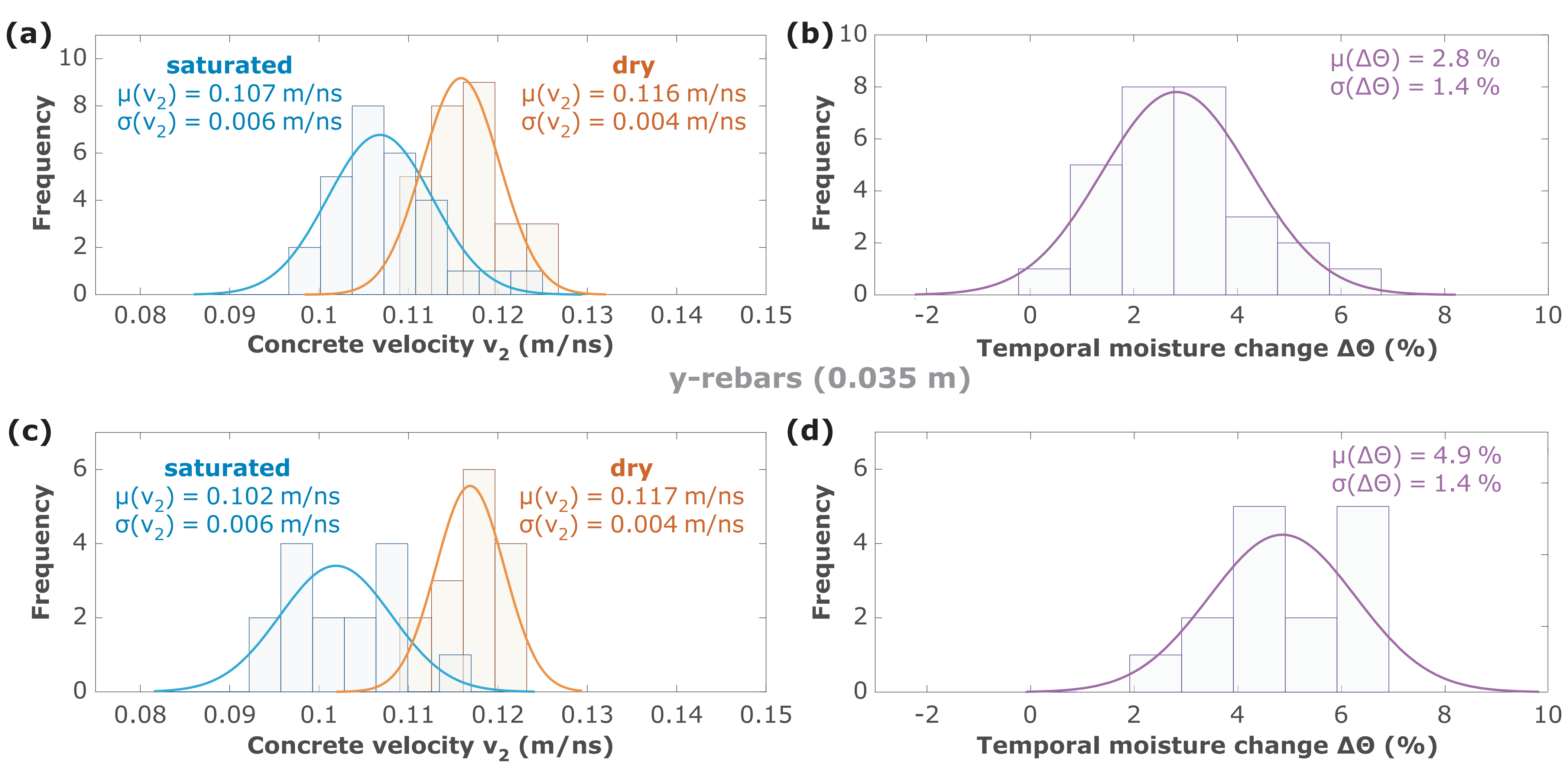
where: t - traveltime, X_m - antennae midpoint, X_0 - migration point, X_{off} - offset, τ - two-way zero-offset time

  (3) Extract objective function Φ defined as maximum energy in apex of diffraction hyperbola after diffraction summation



- Non-unique grid-search result (v_2 and t_0) constrained by velocity-dependent time-zero function t_0^{ap} calculated using rebar depth
- Uncertainty estimates for model parameters based on signal-to-noise ratio estimated from data after diffraction summation
- t_0 fixed at mean value for following analyses
- v_2 extracted at corresponding maximum value of Φ

4.3 Results and interpretation



- Velocity analysis applied to hyperbolas originating from rebars at two different depth levels recorded on dry and saturated specimen
- **(a, c)** Mean velocity $\mu(v_2)$ for dry specimen increased for both depth levels, $\mu(v_2)$ for saturated specimen decreases with depth, standard deviation $\sigma(v_2)$ for saturated specimen increased for both depth levels
- Variation of v_2 at specific monitoring time step smaller than uncertainty of ~±9% associated with individual values of v_2

- Temporal moisture changes ΔΘ inferred using three-component formulation of CRIM model
- **(b)** Trend and magnitude of $\mu(\Delta\Theta)$ in uppermost 0.028 m agree with capacitive measurements using a DNS-Denzel G822 moisture sensor showing $\mu(\Delta\Theta) \approx 1.9\%$ in uppermost ~0.02 m
- **(b, d)** Trend of increasing $\mu(\Delta\Theta)$ with depth and its magnitude reasonable considering gravimetric measurements showing absolute moisture change of ~7%

5. Discussion and conclusions

Our study reveals the potential and limitations of GPR velocity analysis in reinforced concrete buildings such as bridges. The investigated realistic geometry causes traveltime differences to be small (high-velocity cover and shallow rebars), restricts the width of diffraction hyperbolas for a reliable analysis (rebar spacings), and limits the vertical resolution. Therefore, the uncertainty associated with the concrete velocity extracted from a single diffraction hyperbola ranges in the order of ±9% and is higher than the spatial velocity variation observed at a specific monitoring time step. Thus, given common geometries and using typical GPR frequencies, a determination and quantification of typical moisture changes in concrete of a few percent is not feasible by analyzing single diffraction hyperbolas. However, our analysis reveals a mean temporal trend of increasing moisture content related to the water saturation at two different depths of the specimen. These results generally agree with independent capacitive and gravimetric measurements of concrete moisture. Given laboratory-like conditions, our results can be considered to show the resolvable limit of an on-site practical investigation of moisture changes using a diffraction-based velocity analysis.

References and further reading

N. Allroggen, J. Tronicke, M. Delock and U. Böniger, "Topographic Migration of 2D and 3D ground-penetrating radar data considering variable velocities," Near Surface Geophysics, vol. 13, pp. 253–259, 2015.

A. Kalogeropoulos, J. van der Kruk, J. Hugenschmidt, S. Busch and K. Merz, "Chlorides and moisture assessment in concrete by GPR full-waveform inversion," Near Surface Geophysics, vol. 9, pp. 277–285, 2011.

R. Yelf, "Where is true time zero?," Electromagnetic Phenomena, vol. 7, pp. 158–163, 2006.

Ö. Yilmaz and R. Chambers, "Migration velocity analysis by wave-field extrapolation," Geophysics, vol. 49(10), pp. 1664–1674, 1984.