Engineering Evaluation of Satellite InSAR for Mine Tailings Dam Resilience and Early Warning Systems

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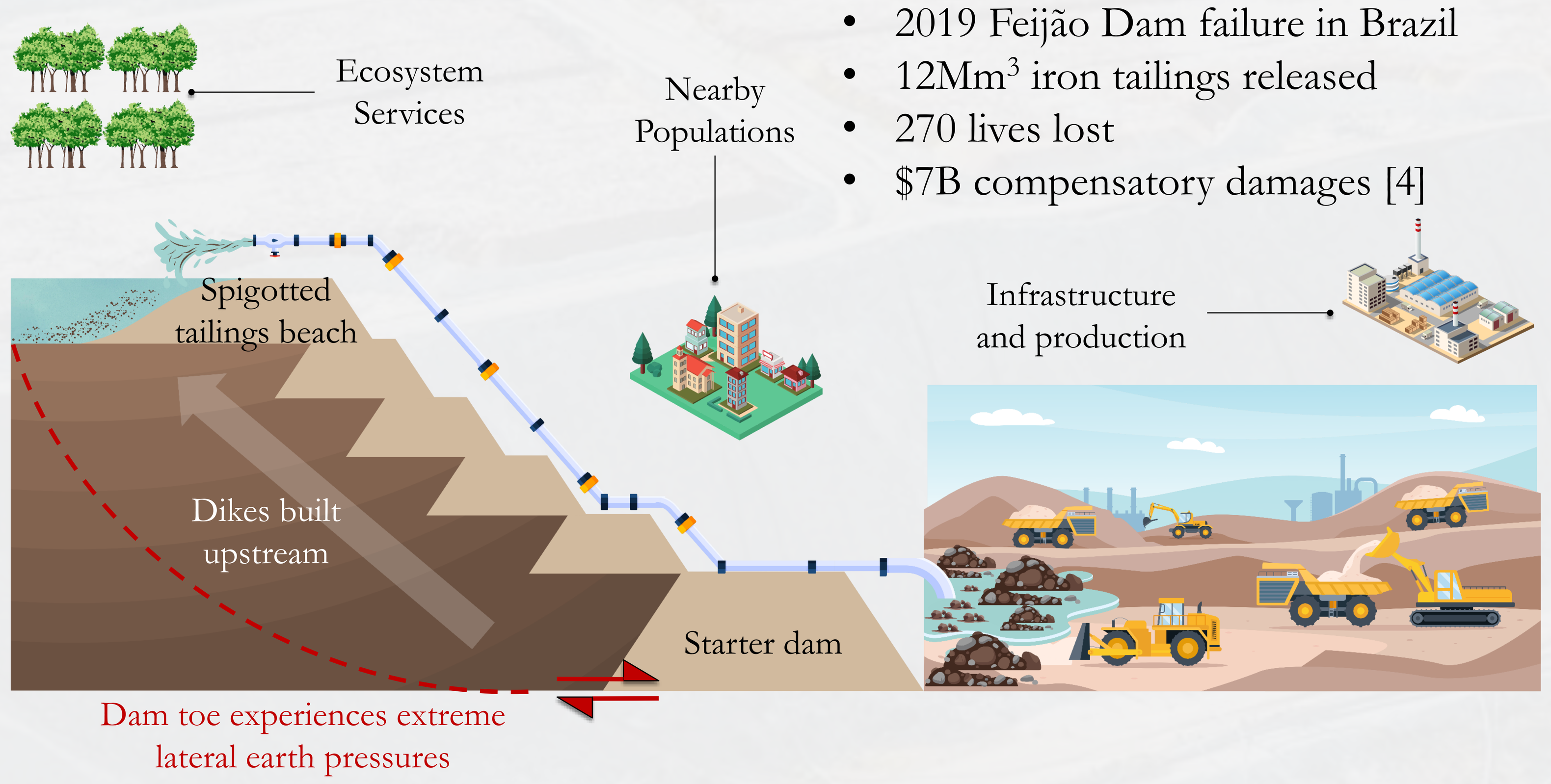
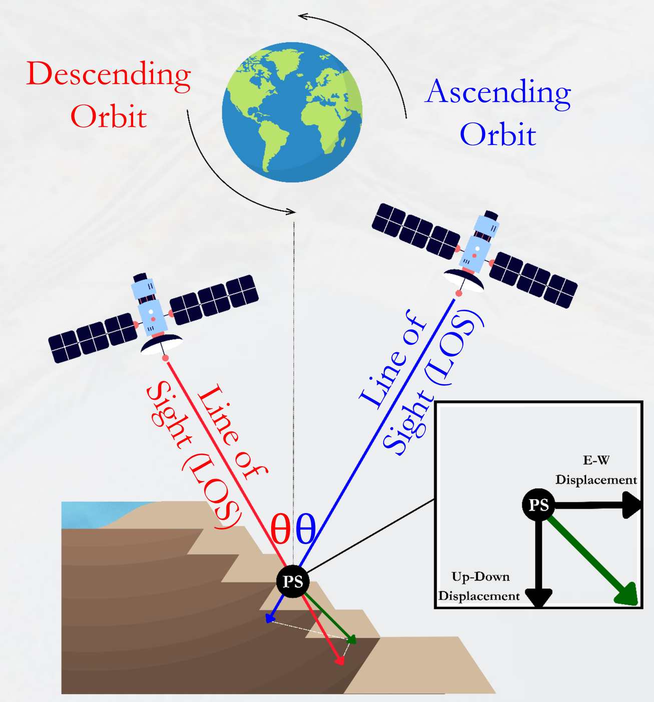
Motivation

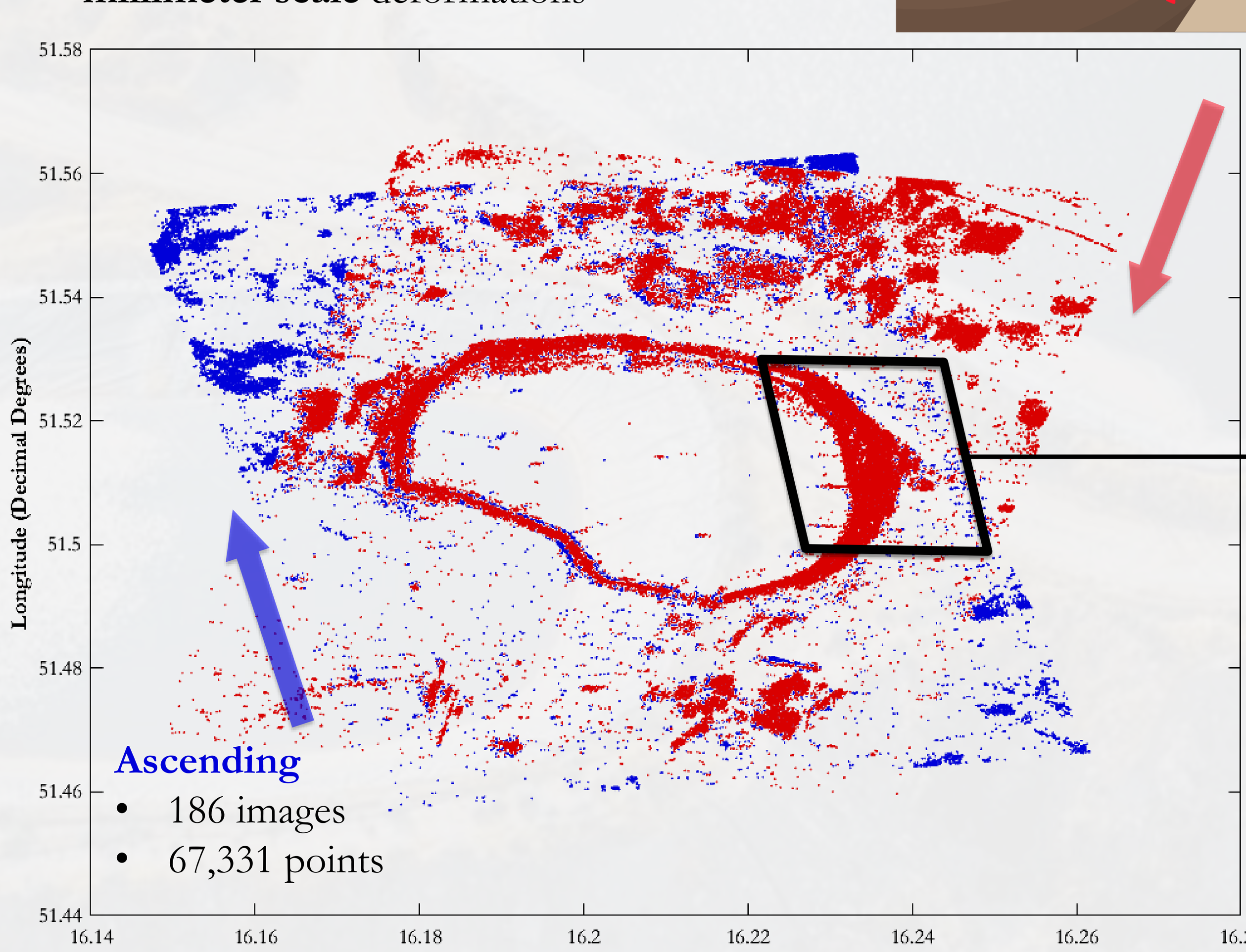
- Tailings are residues of ore mining
- Typically: 200x more tailings than extracted metal [1]
- Upstream Tailings Dam construction
  - Cost efficient; least stable
  - Majority globally
  - Slurry transport from source
  - Hydraulic deposition
- **Tailings Dams are the largest man-made structures on earth**
  - More than 1700 worldwide [2]
  - 70% are owned by 15 companies
  - 57% are high-risk
  - 37 major failures in last 10 years
  - All are completely uninsured [3]
- **Tailings Dams create massive risks:**
  - 2019 Feijão Dam failure in Brazil
  - 12Mm³ iron tailings released
  - 270 lives lost
  - $7B compensatory damages [4]



Remote Sensing of Ground Deformations

- Synthetic Aperture Radar (SAR) is a microwave imaging system
  - Cloud-penetrating
  - Equally effective in the dark
  - Centimetric wavelengths
- InSAR (Interferometric SAR) is a multitemporal post-processing method for tracking ground surface movements
  - Use Persistent Scatterers (PS)
  - Ground targets with constant electromagnetic signatures
  - Remove other phase effects to detect **millimeter scale** deformations

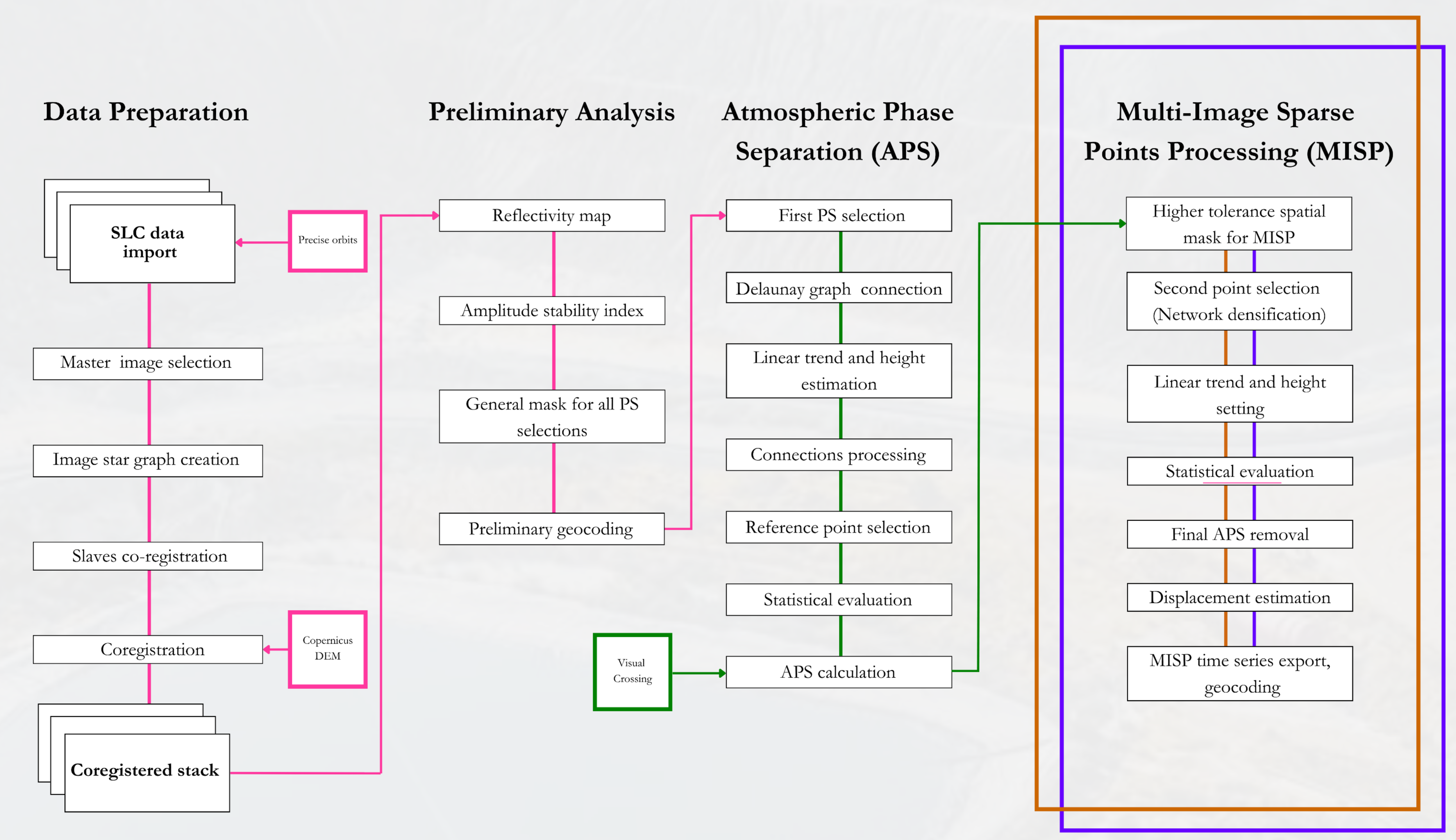




Main Findings

1. **Ground surveys of vertical and lateral movements are in very strong agreement with InSAR velocity data.**
2. **InSAR measurements provide a more complete profile of the underlying sliding mechanism the case study of Zelazny Most.**
3. **More case studies are needed to link surface movements to deformation mechanisms within the soil mass in order to fully assess the accuracy/resolution of InSAR data.**

Methods



$$\Delta\varphi(p) = \Delta\varphi_{i,k}^{flat}(p) + \Delta\varphi_{i,k}^{atmo}(p) + \Delta\varphi_{i,k}^{height}(p) + \Delta\varphi_{i,k}^{disp}(p)$$

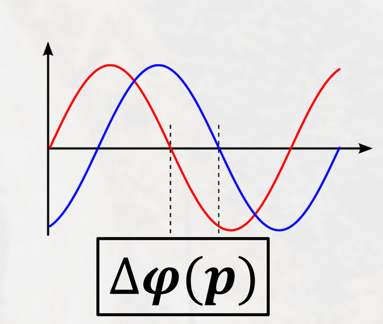
(1) $\Delta\varphi_{i,k}^{flat}(p) =$ Sentinel-1 orbital data, Copernicus DEM

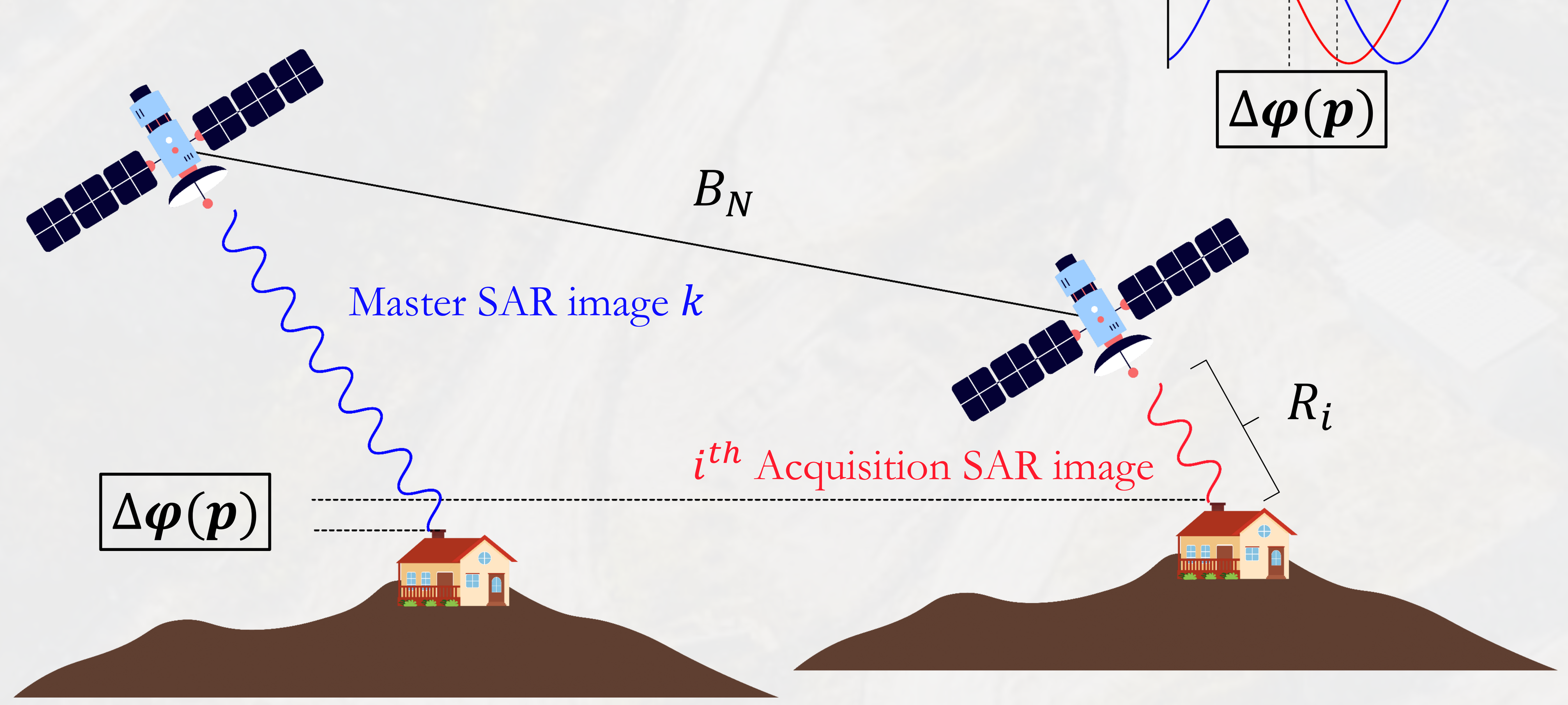
(2) $\Delta\varphi_{i,k}^{atmo}(p) =$ weather from Visual Crossing

(3) $\Delta\varphi_{i,k}^{height}(p) = \frac{4\pi}{\lambda}\frac{B_{N,i}}{R_k}\frac{\Delta h_p}{\sin\theta}$

(4) $\Delta\varphi_{i,k}^{disp}(p) = \frac{4\pi}{\lambda}\Delta v_p B_{T,i}$

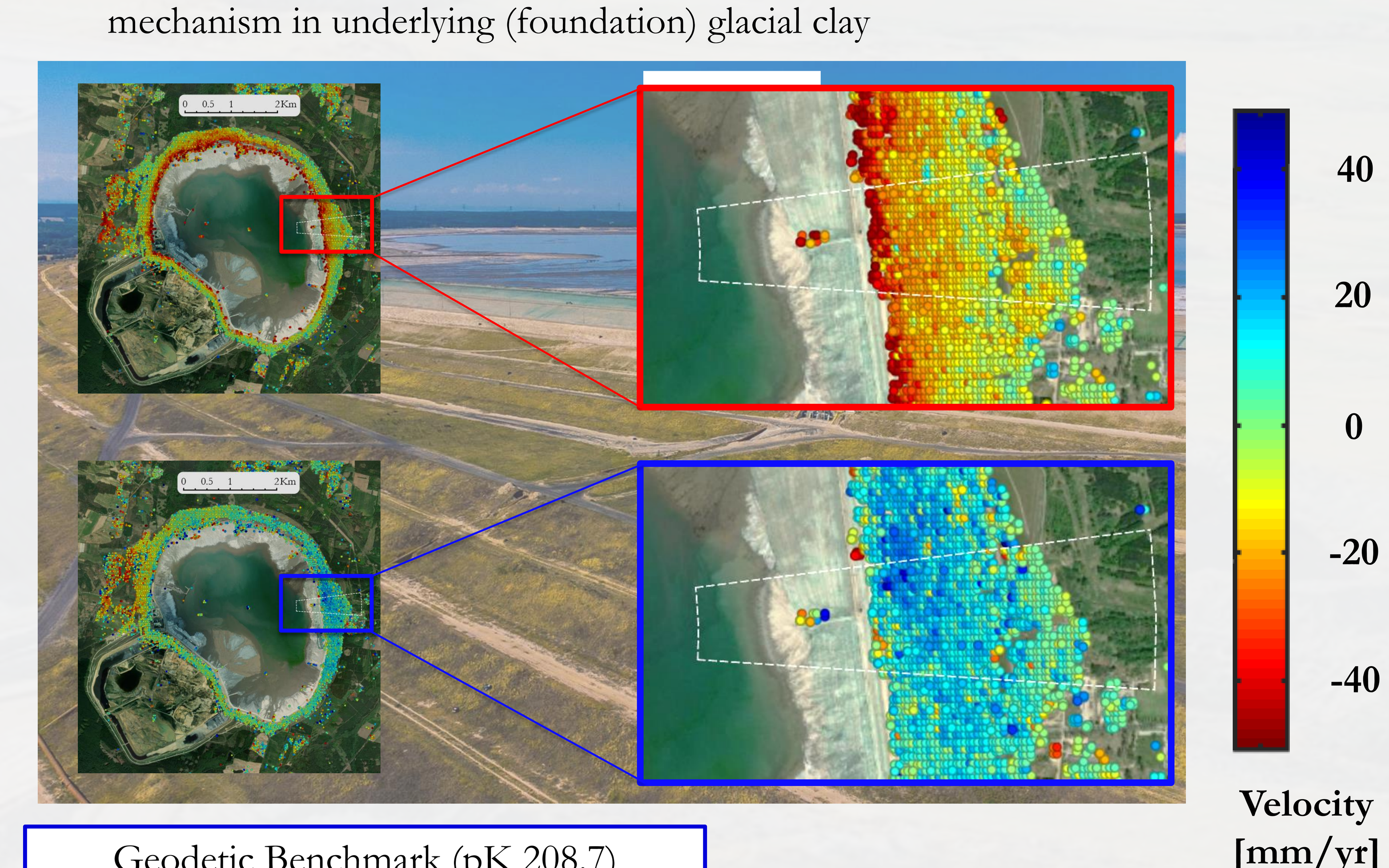
(5) $\gamma(\Delta h_p, \Delta v_p) = \frac{1}{N}\sum_{i=1}^{N} e^{j\left(\Delta\varphi_i - \frac{4\pi}{\lambda}\frac{B_{N,i}}{R_k}\frac{\Delta v_p}{\sin\theta}\right)}$

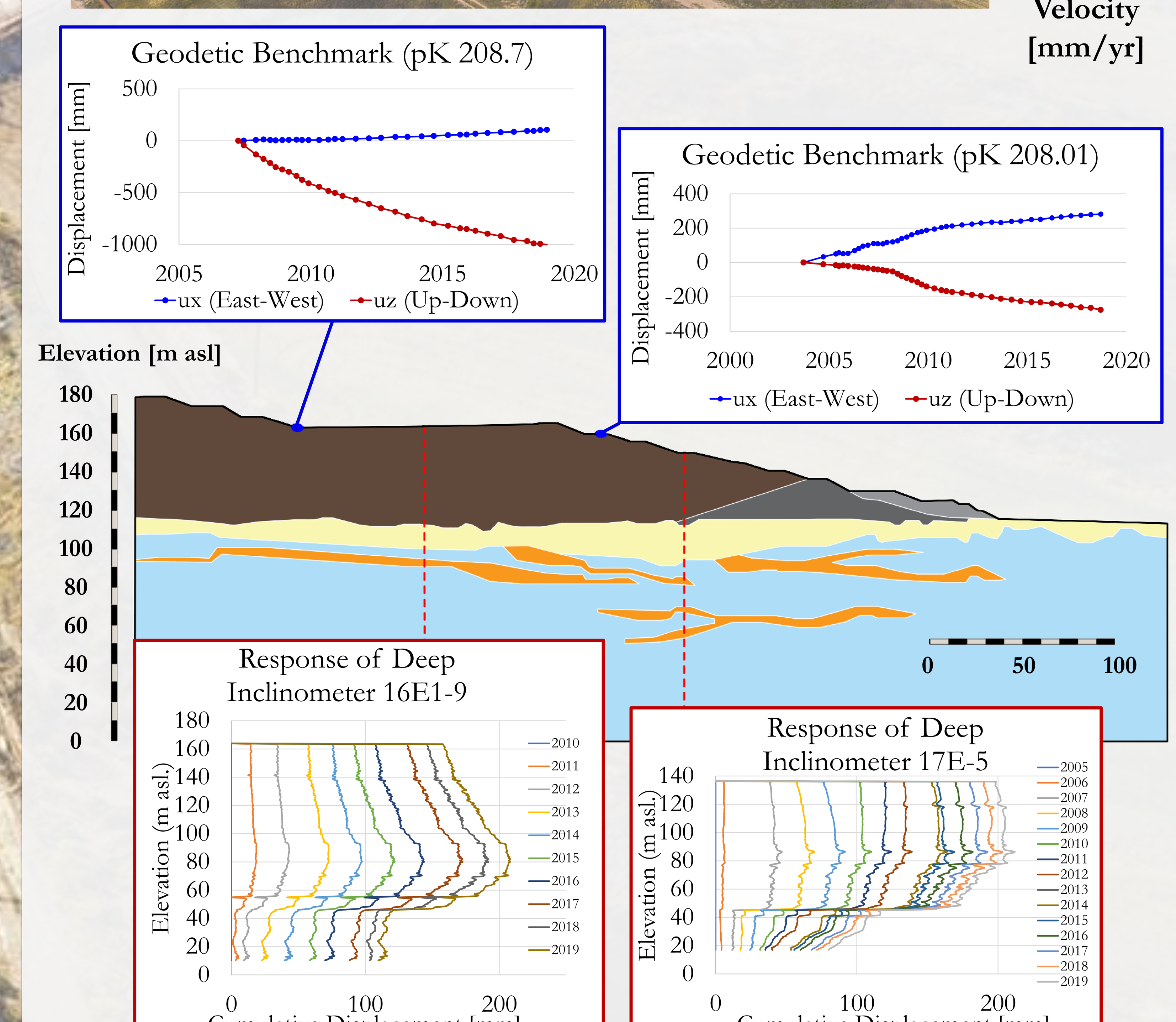




Results (Case Study of Zelazny Most)

- **InSAR ground-truthing is possible for site-specific reasons**
  - Closely monitored with publicly-available surface and embedded instrument measurements for more than 15 years
  - Lateral spreading of the ring dam structure due to a translational sliding mechanism in underlying (foundation) glacial clay





References

[1] D. Kossoff, et al., (2017) "Mine tailings dams: Characteristics, failure, environmental impacts, and remediation," Applied Geochemistry, Volume 51, Pages 229-245

[2] Warburton, M., et al., (2019, December 18). "The looming risk of tailings dams." Reuters.

[3] Franks, D.M.. et al. (2021) "Tailings facility disclosures reveal stability risks," Sci Rep 11, 5353.

[4] Jamiolkowski, M. (2014) "Soil mechanics and the observational method: Challenges at the Zelzny Most copper tailings disposal facility," Géotechnique, 64(8), 590-619.

[5] International Council on Mining and Metals (ICMM). (2022). "Tailings Reduction Roadmap."