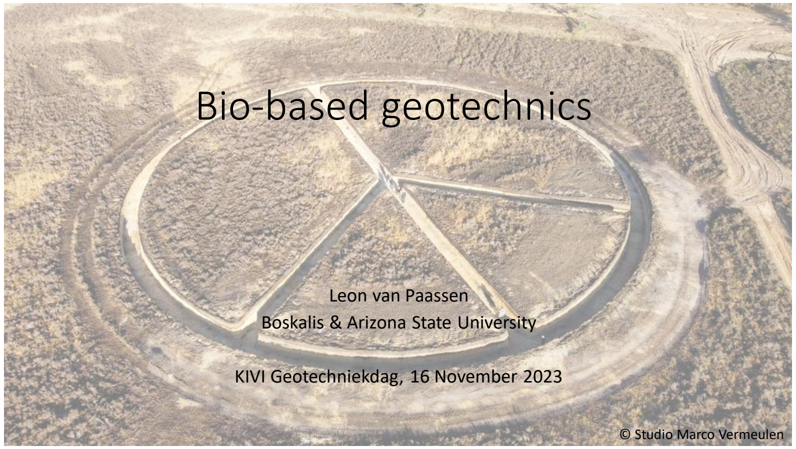


Bio-based geotechnics

Leon van Paassen
Boskalis & Arizona State University

KIVI Geotechniekdag, 16 November 2023

Bio-based geotechnics

"Learn from nature to develop new solutions for geotechnical and geo-environmental engineering applications using biological processes, biomaterials, or bio-inspired design methods, to mitigate the impact of human activities on the environment"

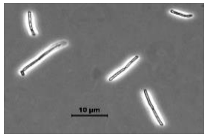
Pinnacle Desert, Western Australia

Biogrout: Ground improvement based on Microbially Induced Carbonate Precipitation (MICP)

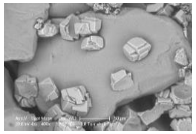
Urease
(Sporosarcina Pasteurii)

$$CO(NH_2)_2 + CaCl_2 + 2H_2O \longrightarrow 2\ NH_4Cl + CaCO_3\ (s)$$

Urea



Sporosarcina pasteurii



$CaCO_3$ crystals

GeoDelft

Whiffin, V. S., Van Paassen, L. A., & Harkes, M. P. (2007). Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiology Journal*, *24*(5), 417-423.

TU Delft

VWS Geotechniek

Scale-up experiments

10 cm 5 m 1m^3 100m^3

1D 3D

GeoDelft

Van Paassen, L. A., Harkes, M. P., Van Zwieten, G. A., Van der Zon, W. H., Van der Star, W. R. L., & Van Loosdrecht, M. C. M. (2009). Scale up of BioGrout: a biological ground reinforcement method. In *Proceedings of the 17th international conference on soil mechanics and geotechnical engineering* (pp. 2328-2333).

TU Delft

VWS Geotechniek

Scale-up experiments

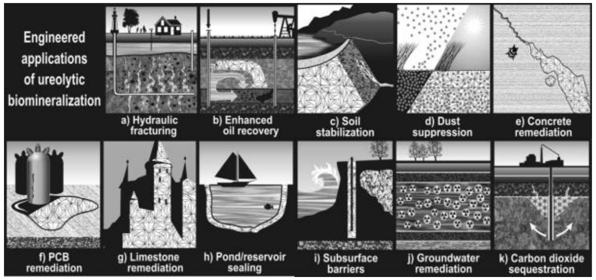
40m³ solidified, but heterogeneous

GeoDelft

Van Paassen, L. A., Ghose, R., van der Linden, T. J., van der Star, W. R., & van Loosdrecht, M. C. (2010). Quantifying biomediated ground improvement by ureolysis: large-scale biogrout experiment. *Journal of geotechnical and geoenvironmental engineering*, *136*(12), 1721-1728.

TUDelft

Envisioned Engineering Applications



GeoDelft

Phillips, A. J., Gerlach, R., Lauchnor, E., Mitchell, A. C., Cunningham, A. B., & Spangler, L. (2013). Engineered applications of ureolytic biomineralization: a review. *Biofouling*, *29*(6), 715-733.

TUDelft

Visser & Smit Hanab

First Field Trials 2010

- Stabilizing a borehole for a gas pipeline installation in gravel

GeoDelft

Van Paassen, L. A. (2011). Bio-mediated ground improvement: from laboratory experiment to pilot applications. In *Geo-Frontiers 2011: Advances in Geotechnical Engineering* (pp. 4099-4108).

TUDelft

Visser & Smit Hanab

First Field Trials 2010

- 4x4x50 m³ sand and gravel
- 4 to 20 depth
- Injection and Extraction wells in 5 m grid

GeoDelft

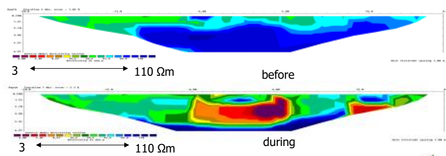
Van Paassen, L. A. (2011). Bio-mediated ground improvement: from laboratory experiment to pilot applications. In *Geo-Frontiers 2011: Advances in Geotechnical Engineering* (pp. 4099-4108).

TUDelft

Visser & Smit Hanab

First Field Trials 2010

- $4x4x50\ m^3$ sand and gravel
- 4 to 20 depth
- Injection and Extraction wells in 5 m grid
- 1 day injection 6 days extraction
- Monitoring, sampling and testing methods



GeoDelft

Van Paassen, L. A. (2011). Bio-mediated ground improvement: from laboratory experiment to pilot applications. In *Geo-Frontiers 2011: Advances in Geotechnical Engineering* (pp. 4099-4108).

TU Delft

Visser & Smit Hanab

First Field Trials 2010

- $4x4x50\ m^3$ sand and gravel
- 4 to 20 depth
- Injection and Extraction wells in 5 m grid
- 1 day injection 6 days extraction
- Monitoring, sampling and testing methods
- Successful installation

GeoDelft

Van Paassen, L. A. (2011). Bio-mediated ground improvement: from laboratory experiment to pilot applications. In *Geo-Frontiers 2011: Advances in Geotechnical Engineering* (pp. 4099-4108).

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Conclusions after MICP Field trials 2010

- MICP by urea hydrolysis can be used to stabilize soils
- Injection, mixing, monitoring and sampling methods are available
- Empirical correlations are available.
- Many possible applications.

But…

- Limited field evidence, control, homogeneity
- Costs: about €400 per m^3 soil)
  - Resources (Urea and Calcium chloride)
  - Ammonium chloride removal
  - Cultivation of bacteria
- Environmental impact?

Optimize the process

Alternative applications

Alternative MICP processes

Alternative products

GeoDelft

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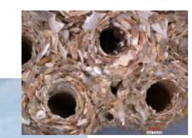
Alternative applications

biogeocivil

Applications which require **low strength** and **limited homogeneity**

- Liquefaction mitigation
- Erosion control
- Internal erosion mitigation
- Scour protection
- Dust supression
- Environmental barriers
- **Beach stabilization**



Deltares

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Alternative applications

- Borehole Stabilization in Beuningen, Netherlands
  (Van der Star et al , 2010)
- Increase liquefaction resistance at Lower Granite Dam, Washington, USA
  (Burbank et al 2011)
- Immobilisation of metal contaminants in Rifle, Colorado, USA
  (Smith et al 2012)
- Slope stabilization in Toronto, Canada, Oirschot, Netherlands and in Nice, France
  (Esnault et al 2015, Chen et al. 2020)
- Wind erosion mitigation, British Columbia, Canada and Ninxia Hui, China
  (Gomez et al 2015, Meng et al 2021)
- Fracture sealing in Jasper, Alabama, USA and Birmingham, United Kingdom
  (Phillips et al 2016, Cuthbert et al 2013)
- Beach erosion mitigation, Yogyakarta, Indonesia
  (Daryono et al 2019)

Beuningen, 2010

Oirschot, 2021

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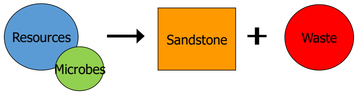
Alternative processes

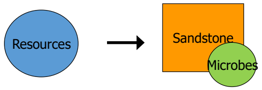
Urea hydrolysis — *Sporosarcina pasteurii*

ureum + calcium chloride → $CaCO_3$ + ammonium chloride



Denitrification — Denitrifying bacteria

calcium-fatty acid + calcium nitrate → bacteria + $CaCO_3$ + N_2(g)



Van Der Star, W. R., Taher, E., Harkes, M. P., Blauw, M., Van Loosdrecht, M. C., & Van Paassen, L. A. (2010, November). Use of waste streams and microbes for in situ transformation of sand into sandstone. In International Symposium on Ground Improvement Technologies and Case Histories, ISGI'09 (pp. 177-182).

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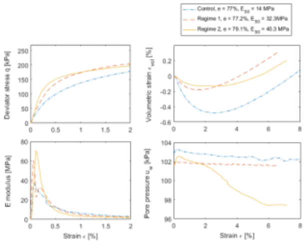
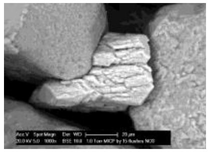
MICP by denitrification

- Low concentrated substrates
- Requires multiple (3-15) flushes to reach 1 % CaCO3
- Relatively slow (1 month)
- Potential clogging with gas, biomass and minerals





Pham, V. P., van Paassen, L. A., van der Star, W. R., & Heimovaara, T. J. (2018). Evaluating strategies to improve process efficiency of denitrification-based MICP. *Journal of Geotechnical and Geoenvironmental Engineering*, *144*(8), 04018049.

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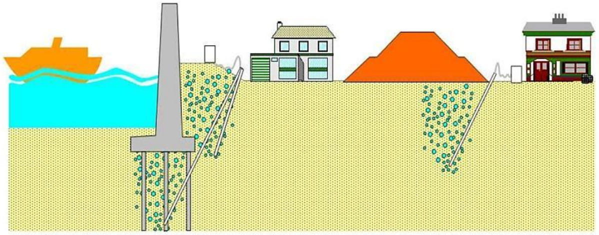
Alternative products: biogenic gas



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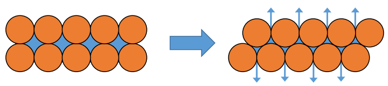
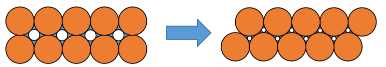
Desaturation can mitigate liquefaction by damping pore pressures

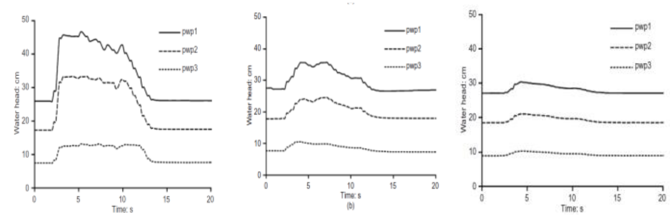
Fully saturated soil



Partially saturated soil



Desaturation can mitigate liquefaction by damping pore pressures



D_r = 52%, S_r = 100% D_r = 51%, S_r = 95% D_r = 43%, S_r = 80%

He, J., & Chu, J. (2014). Undrained responses of microbially desaturated sand under monotonic loading. *Journal of Geotechnical and Geoenvironmental Engineering*, *140*(5), 04014003.

Comparing precipitation and desaturation…

Precipitation (MICP) requires:
- 1-3% $CaCO_3$ cementation,
- 25-70 kg substrate /m³
- in 3-10 flushes

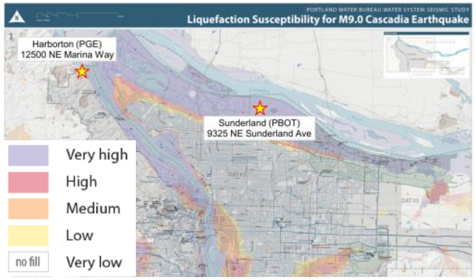
Desaturation (MID) requires:
- 10-20% N_2 desaturation,
- 0.7-1.5 kg substrate/m³
- in 1 flush

Desaturation requires 40 times less substrates!

But,…. How is the gas distributed?
Is the desaturation persistent?

O'Donnell, S. T., Rittmann, B. E., & Kavazanjian Jr, E. (2017). MIDP: Liquefaction mitigation via microbial denitrification as a two-stage process. I: Desaturation. *Journal of Geotechnical and Geoenvironmental Engineering*, *143*(12), 04017094.

Field trials in Portland 2019

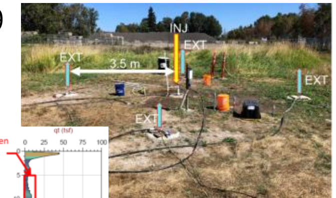


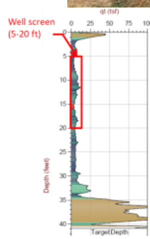
Moug, D., Khosravifar, A., Preciado, A., Sorenson, K., Stokoe, K., Menq, F., Zhang, B., Van Paassen, L., Kavazanjian, E., Stallings-Young, E. & Wang, Y. (2020) Field Evaluation of Microbially Induced Desaturation for Liquefaction Mitigation of Silty Soils, 17th World Conference of Earthquake Engineering, Sendai, Japan

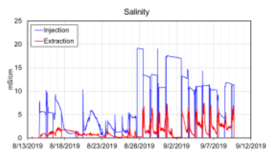
Portland State University

Field trials in Portland 2019

- Treatment radius 3.5 m
- Targeted soil volume 200 m^3
- 70 m3 substrate solution injected
- Mainly low plasticity silt







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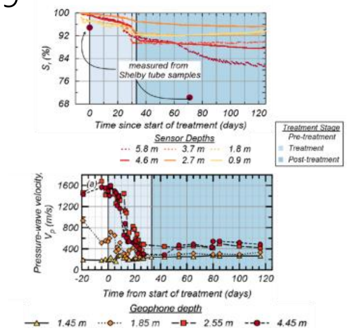
ASU Arizona State University

Field trials in Portland 2019

- Desaturation and persistence is measured in situ using:
  - Teros 12 sensors
  - Cross-hole pressure wave velocity
- Soil desaturates to target level within 4 weeks of treatment
- Remains desaturated for at least 120 days (and monitoring still ongoing)



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Sorenson, K., Preciado, A.M., Moug, D., Khosravifar, A., Van Paassen, L.A., Kavazanjian, E., Stokoe, K. and Menq, F. (2021) Field Monitoring of the Persistence of Microbially Induced Desaturation for Mitigation of Earthquake Induced Soil Liquefaction in Silty Soil, In: Proceedings of the ASCE San Fernando Earthquake Conference – 50 Years of Lifelines Engineering

ASU Arizona State University

Field trials in Portland 2019

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ASU Arizona State University

Conclusions after MID Field Trials 2019

- MID (and MICP) can be used as a bio-based ground improvement method
- New injection, mixing, monitoring and sampling strategies available
- Costs < €100 per m^3

But still…

- Limited evidence for liquefaction resistance at field scale?
- QA/QC?
- Homogeneity?
- Persistence?
- Environmental impact?

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Future opportunities

- Demonstrated Potential of Bio-based ground improvement methods
- But commercialization requires:
  - competitive advantage
  - the right application
  - industry involvement and
  - field scale validation.
- Many more processes and applications to explore

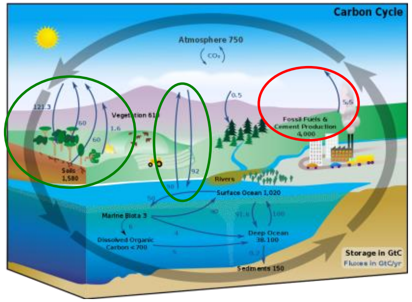
Boskalis

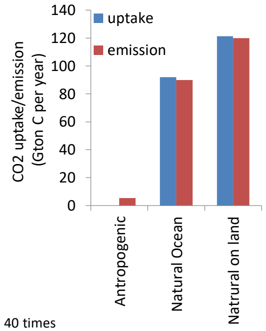
Future opportunities

- Use MID to improve the efficiency of dynamic compaction
- Worms or plants to accelerate consolidation of soft sediments
- Worms, shrimps, mangroves and corals for ecological restoration and coastal protection

Boskalis

Future opportunities





Nature's potential for carbon uptake is up to 40 times higher than the total anthropogenic carbon emissions

Boskalis

Acknowledgements

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- Wouter van der Star, Deltares
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