Recent Trinity College Dublin environmental-geotechnics research and collaborations, with focus on greener economy by sustainable technologies

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Overview

- Natural polymers (biopolymers) for grouting
- Microbial-induced carbonate precipitation (MICP) for grouting/spraying
- Nanomaterials: nanosilica (NS) and nanoclay (NC) for soil mixing/grouting
- Overview of other novel ground improvement/remediation for:
  - Expansive soil
  - Soil remediation/adsorption of contaminants
  - Liquefaction resistance
  - Microplastics in soil/groundwater (our latest research area)

To finish with vacuum consolidation and granular anchors research

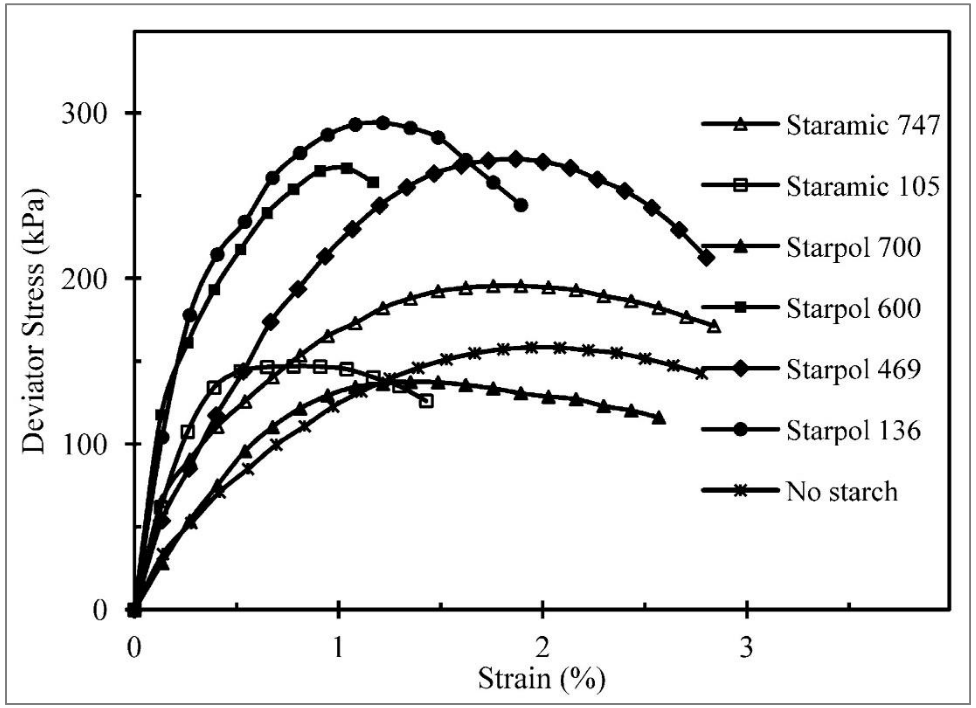
1, Biopolymers: environmentally friendly, sustainable grouting materials

Our early work (Khatami and O'Kelly, 2013)

- *Guidelines for selecting potentially useful biopolymers for soil improvement*

Plus, investigated compatibility of Fontaine-bleau sand with 1–4% agar and **6 modified starches** (0.5–1%)

Starpols 600 & 136 at same **agar** concentration (1%) significantly increase cohesion/stiffness



Unconfined compression
Sand + 1% agar + 0.5% starch

Khatami H.R. and O'Kelly B.C., 2013, Improving mechanical properties of sand using **biopolymers**, *Geotechnical and Geoenvironmental Engineering*, 139(8): 1402–1406.

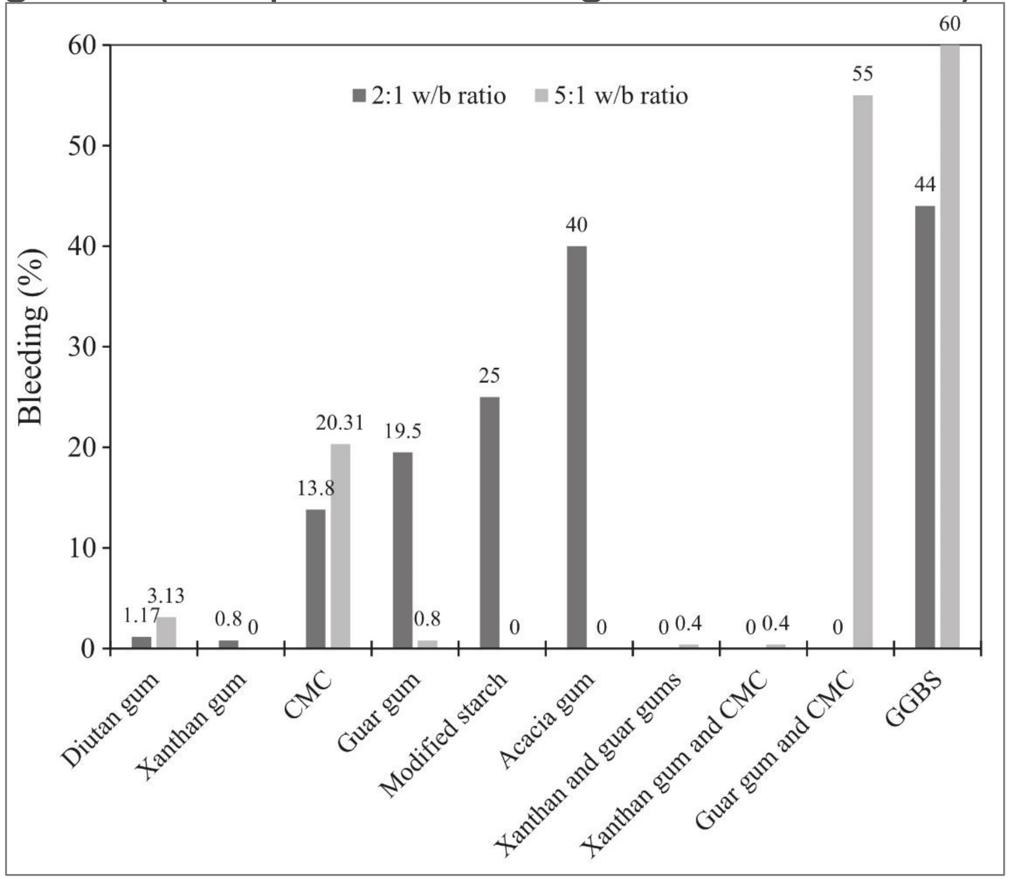
Biopolymers (ctd.) Recent contribution (Khatami and O'Kelly, 2018)

Goal: *find additives that keep solids in suspension for reasonable period demanded by grouting application* (=> increase zeta potential of fine grout particles)

- **Superfine GGBS cement** at 2:1 & 5:1 water/binder ratio; various biopolymers investigated

Biopolymer	Concentration (percentage by mass of water)
Diutan gum (DG)	0.25%
Carboxymethylcellulose (CMC)	0.25% (for 2:1 w/b)–1.0% (for 5:1 w/b)
Xanthan gum (XG)	0.25% (for 2:1 w/b)–1.0% (for 5:1 w/b)
Guar gum (GG)	0.25% (for 2:1 w/b)–1.0% (for 5:1 w/b)
Acacia gum (AG)	1.0% and 2.0% (for 2:1 w/b)
Starch	0.5% (for 2:1 w/b)
Xanthan gum and CMC	0.25% XG and 0.25% CMC (for 5:1 w/b)
Xanthan gum and guar gum	0.25% XG and 0.25% GG (for 5:1 w/b)
Guar gum and CMC	0.25% GG and 0.25% CMC (for 5:1 w/b)

Below: bleeding tests on GGBS–biopolymer grouts (acceptable bleeding considered <5%)



Diutan gum & **xanthan gum** gave highest performance in bleeding prevention at 0.25–1.0 wt%; **xanthan gum** provided synergy with both guar gum & CMC.

Khatami, H. and O'Kelly, B.C., 2018, Prevention of bleeding of particulate grouts using biopolymers, *Construction and Building Materials*, 192: 202–209.

2, MICP (with Dr. S.M.A. Zomorodian, Shiraz University)

Goal: *For loose sand, improve strength & stiffness, without significant permeability (k) reduction*

- Achieve homogeneous calcite deposition throughout treated soil mass

Two loose medium quartz sands, different concentrations of bacterial cell (*S. pasteurii*) and urea–$CaCl_3$ solutions, investigated various injection protocols

- Measured strength, stiffness and permeability coefficient (k), plus SEM, for treated specimens (Shahrokhi-Shahraki et al., 2015)

Staged injection including retention periods, with pressure head applied during injection of bacterial solution, proved most effective

k values reduced by up to one order of magnitude => method tailored, so as to not significantly affect drainage capacity of treated sand media

Shahrokhi-Shahraki R., Zomorodian S.M.A., Niazi A. and O'Kelly B.C., 2015, Improving sand with microbial-induced carbonate precipitation, *Proceedings of the ICE – Ground Improvement*, 168(3): 217–230.

MICP (ctd.): *Reducing the hydraulic erosion of sand* (Amin et al., 2017)

- Erodibility parameters of dense, medium quartz sand, treated with different injection strategies, investigated using erosion-function apparatus (EFA) and SEM

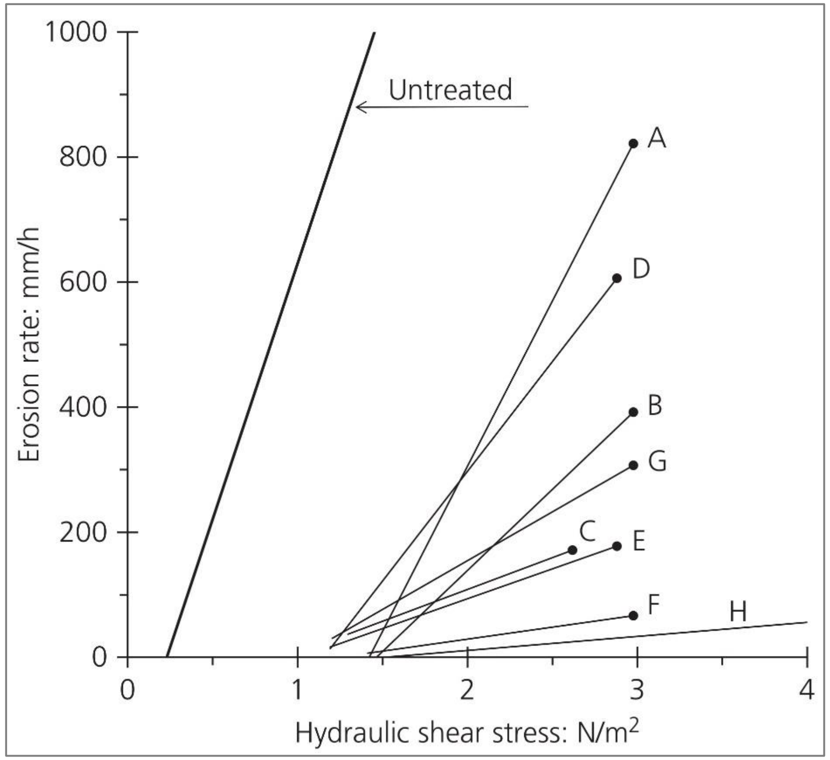
Table 1

	Treatment							
Day	A	B	C	D	E	F	G	H
1	Inject bacteria	Inject bacteria	Inject bacteria	Inject bacteria	Inject bacteria	Inject bacteria	Inject bacteria	Inject bacteria
2	Cementation (0·5 M)	Cementation (0·5 M)	Cementation (0·5 M)	Cementation (0·5 M)	Cementation (0·75 M)	Cementation (0·5 M)	Cementation (0·5 M)	Cementation (0·5 M)
3	Drainage	Drainage	Inject bacteria	Cementation (0·5 M)	Inject bacteria	Drainage	Drainage	Drainage
4			Cementation (0·5 M)	Drainage	Cementation (0·75 M)			
5			Drainage		Drainage			
9						Inject bacteria	Cementation (0·5 M)	
10						Cementation (0·5 M)	Drainage	
11						Drainage		
15								Inject bacteria
16								Cementation (0·5 M)
17								Drainage
Aeration during injections	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

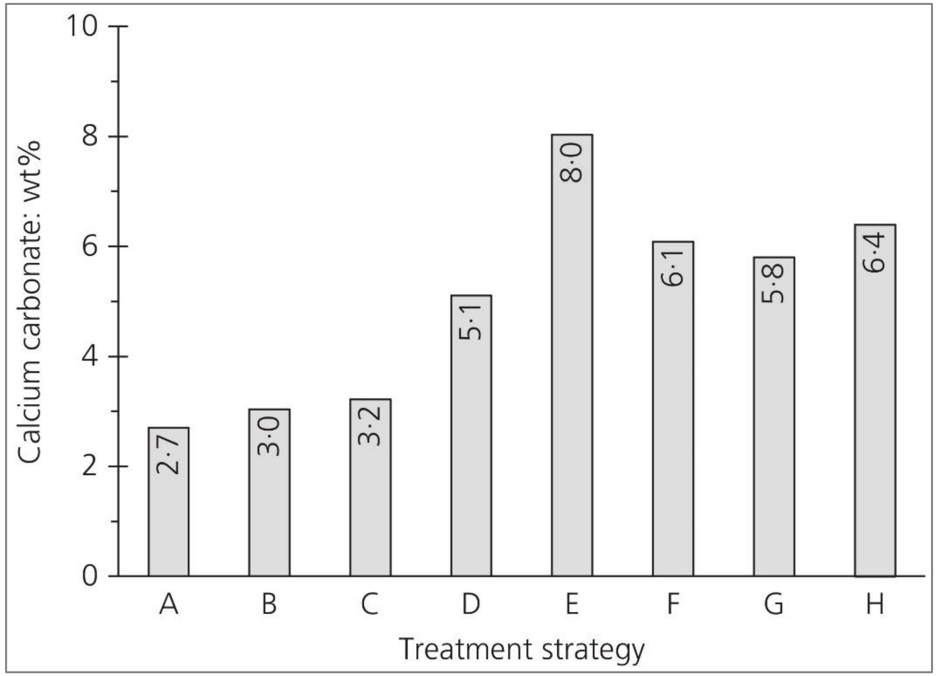
More effective treatment – in terms of greater and more uniform calcite precipitation over test-specimen length – *achieved by aeration during solution injections and incorporating drained stage between the two injection cycles*

Achieved 95% reduction in erodibility and 5-fold increase in critical shear stress, relative to untreated sand

Erosion functions for treatment strategies (A–H: refer to Table 1)



Calcite precipitate distribution recorded over specimen length (A–H: refer to Table 1)



2 injection cycles (each with aeration during injections and 24-h solution retention periods), with 6 d drained stage between cycles, and for 0·5 M cementation solution, produced 6.1 wt% calcite precipitate

Calcite precipitated as larger crystals, accumulating extensively over grain surfaces and formed integrated in pore voids

Amin M., Zomorodian S.M.A. and O'Kelly B.C., 2017, Reducing the hydraulic erosion of sand using microbial-induced carbonate precipitation, *Proceedings of the ICE – Ground Improvement*, 170(2): 112–122.

MICP (ctd.):

Stabilisation of crustal layer to mitigate wind erosion (Zomorodian et al., 2019)

Spray treat sand surface layer with cementation and bacterial solutions mixture, …
Goal, provide necessary bond strength (cohesion) at grain contacts

- Investigated loose medium silica sand, and fine and medium carbonate sands

Determine optimal reagent concentrations for Torvane strength development of crustal sand layer after single- and double-MICP spray treatments (latter applied 6 d after first spray application)

- **Effect of dew formation** on strength development, and **outdoor experiments,** testing efficiency of MICP treatment over 3.5 month curing; strong **temperature-dependence** of MICP process
- Also, ***wind tunnel experiments*** *=> 28-d cured singly-MICP-spray-treated crustal sand layer (using optimum reagent concentrations) found stable to simulated 20 m/s winds measured at 20 cm above layer surface*.

Zomorodian S.M.A., Ghaffari H. and O'Kelly B.C., 2019, Stabilisation of crustal sand layer using biocementation technique for wind erosion control, *Aeolian Research*, 40: 34–41.

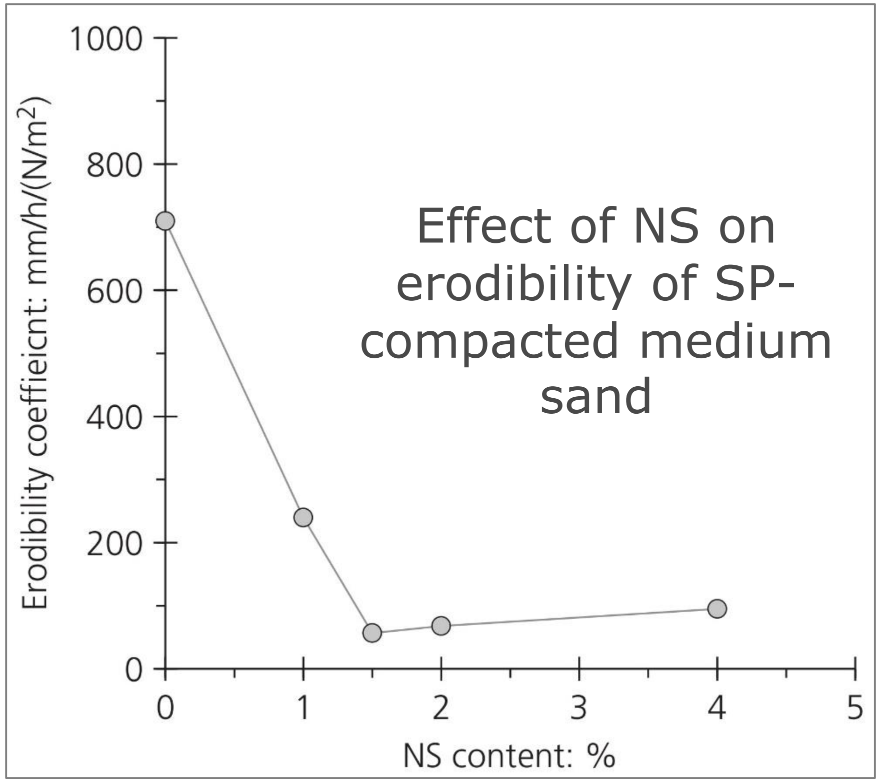
3, Nanomaterials (with Dr. Zomordian, Shiraz Univ.)

Improving hydraulic erosion resistance of sand using ***nano-silica*** (NS) additive (Zomorodian et al., 2019)

- Compacted medium silica sand mixed with 1–4% NS (11–13 nm particle size range) investigated using erosion-function apparatus
- **1·5% NS optimum** amount in terms of greatest erosion resistance; i.e., 92% reduction in erodibility coefficient and 6-fold increase in critical shear stress, also achieved within significantly shorter period compared to traditional cement/lime additives

NS viscous gel property allows mobilisation of effective cohesion (surface bond strength)

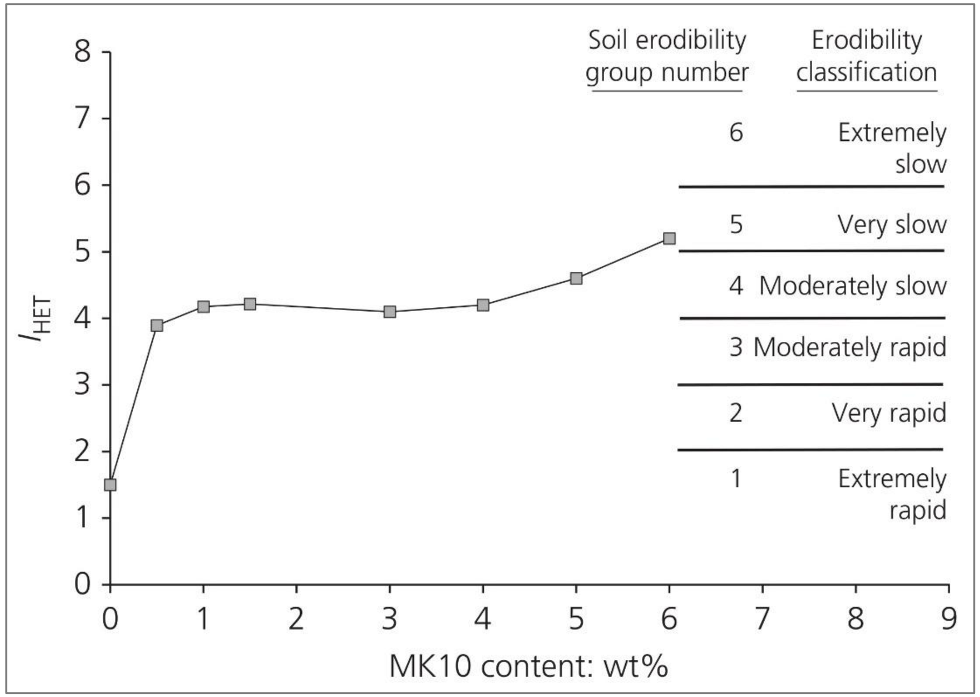
Zomorodian S.M.A., Soleymani A. and O'Kelly B.C., 2019, Improving erosion resistance of sand using nano-silica additive, *Proceedings of the ICE – Ground Improvement*, 172(1): 3–11.



Medium fine sand with CS aqueous gel (Georgiannou et al., 2017)

Improving seepage-induced erosion resistance of silty sand using nanoclay (NC) additive (Zomorodian et al., 2020)

Highly erodible SP-compacted very silty sand, mixed with 0.5–6 wt% montmorillonite K10 (MK10), and investigated using hole-erosion test (HET); compared with 0.25–3% cement



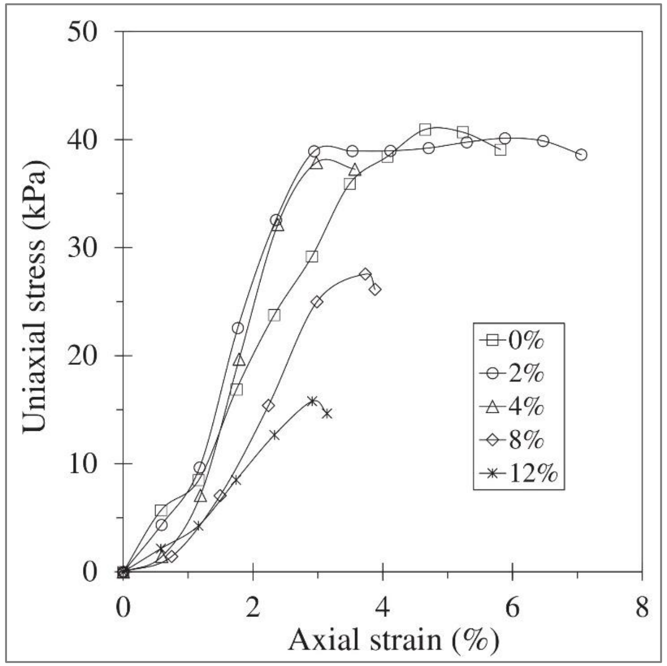
Compared to cement, MK10 additive equally effective at similar wt%; advantage of substantially lower embodied carbon

Effect of MK10 on erodibility of 1-d-cured compacted very silty sand at 13% water content (i = 7·2) => 1% MK10–soil mixture, results in moderately slow erosion

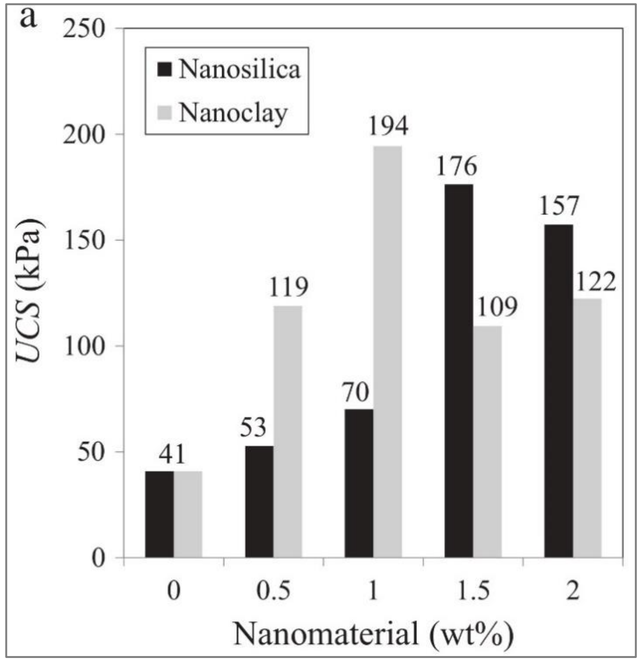
Zomorodian S.M.A., Moghispoor S., O'Kelly B.C. and Babaei S.S., 2020, Improving internal erosion resistance of silty sand using additives, Dams and Reservoirs, 30(1): 29–41.

Zomorodian et al. (2017) *investigated strength/stiffness improvement for clean and kerosene-contaminated compacted sandy lean clay* (CL) soil mixed with 0.5–2.5% **NC** (montmorillonite) and **NS**: particle size ranges of 1–2 and 11–13 nm, respectively

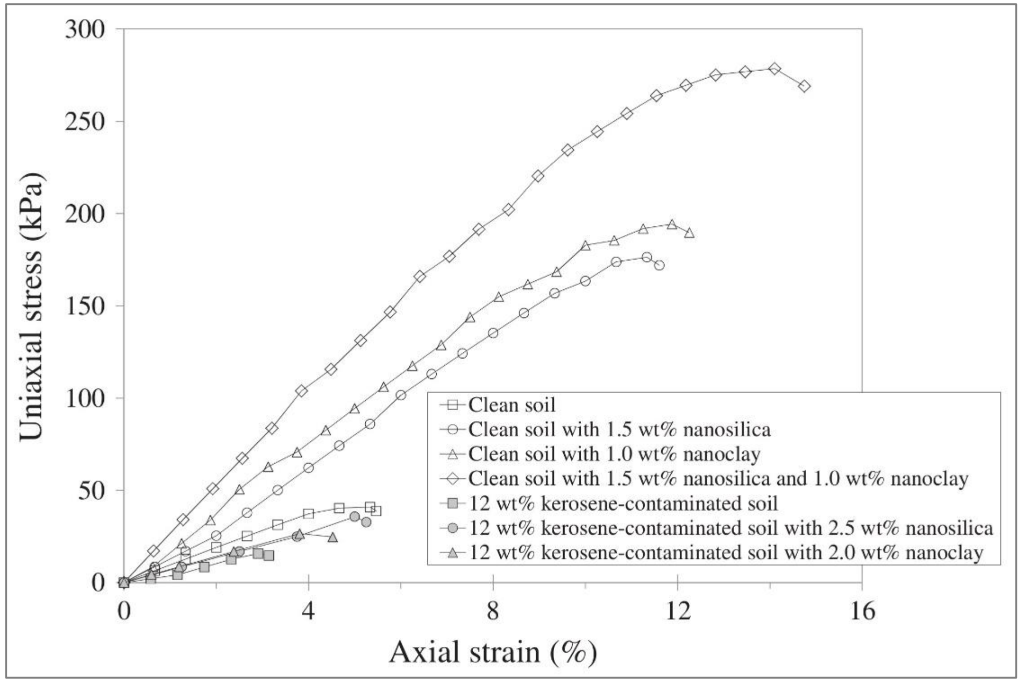
Contamination of soils with oil products can occur during refining, transportation & operation processes



Influence of wt% kerosene on compression strength for CL soil



1 wt% NC additive more efficient in improving strength/stiffness



Zomorodian S.M.A., Shabnam M., Armina S. and O'Kelly B.C., 2017, Strength enhancement of clean and kerosene-contaminated sandy lean clay using nanoclay and nanosilica as additives, *Applied Clay Science*, 140: 140–147.

- Other collaborations … *Investigating **colloidal NS hydrosols** for use as alternative low-viscose grouting material* (medium-dense fine silica sand)

  Ghadr S., Assadi-Langroudi A., Hung C, O'Kelly B.C., Bahadori H. and Ghodsi T., 2020, Stabilization of sand with colloidal nano-silica hydrosols, *Applied Sciences*, 10(15): 5192.

- Effects of ***sulfonated oil (SO) stabiliser** on swell–shrink properties of expansive soil* investigated via cyclic wetting–drying tests: 0.75% SO identified as optimum

  (with PI Dr. Soltani, Federation University, VIC, Australia)

  Soltani A., Raeesi R. and O'Kelly B.C., 2021, Cyclic swell-shrink behaviour of an expansive soil treated with a sulfonated oil, *Proceedings of the ICE – Ground Improvement*.

- Inspired by chemically-assisted sedimentation for potable water production at municipal works, investigated effects of *dilute **aluminum sulfate and polyelectrolyte** solutions* on geotechnical properties of organic clay/silt

  O'Kelly B.C., 2011, Effects of aluminum sulfate and polyelectrolyte solutions on the geotechnical properties of organic clay, *Soils and Foundations*, 51(2): 359–367.

- Using ***Polyhydroxybutrate** (PHB) as a method of soil remediation*…. PHB can be degraded aerobically/anerobically, at rate between up to 1–20 µm/d, adsorbing organic compounds, which are co-metabolized as it degrades.

  Mulvihill, N., 2020, *An Exploratory Analysis of Using Polyhydroxybutrate (PHB) as a Method of Soil Remediation - A Laboratory Investigation*, MAI thesis, University of Dublin, Trinity College Dublin.

- **Microplastics** in soil/groundwater (our newest research area)

- Up to 10% **tire-derived aggregate** (TDA) content reduced swelling potential of **high-expansivity clay soil** to moderate expansivity, while improving strength-related features (TDA gradations = medium/coarse sands)

  Soltani A., Taheri A., Deng A. and O'Kelly B.C., 2020, Improved geotechnical behavior of an expansive soil amended with tire-derived aggregates having different gradations, *Minerals*, 10(10).

- Combining **ground rubber** (GR) **and polyacrylamide** (PAM), the binder, for improving **expansive clay**; *maximum GR of 20%, with 0.2 g/L PAM* deemed optimum

  Soltani A., Deng A., Taheri A. and O'Kelly B.C., 2019, Engineering reactive clay systems by **ground rubber** replacement and polyacrylamide treatment, *Polymers*, 11: 1675.

- **Pulverized waste tires** (PWT: 0, 5, 10, 15, 25 and 100 wt%) **with well graded sand** for **adsorption of contaminants** (**BTEX** components **and heavy metal ions** (Pb^{2+} and Cu^{2+}))

  => **Compacted soil and 5–25% PWT mixture** adequate shear capacity for many load bearing field applications, **used as adsorptive fill material**

  Shahrokhi-Shahraki R., Kwon P.S., Park J., O'Kelly B.C. and Rezania S., 2020, BTEX and heavy metals removal using pulverized waste tires in engineered fill materials, *Chemosphere*, 242: 125281.

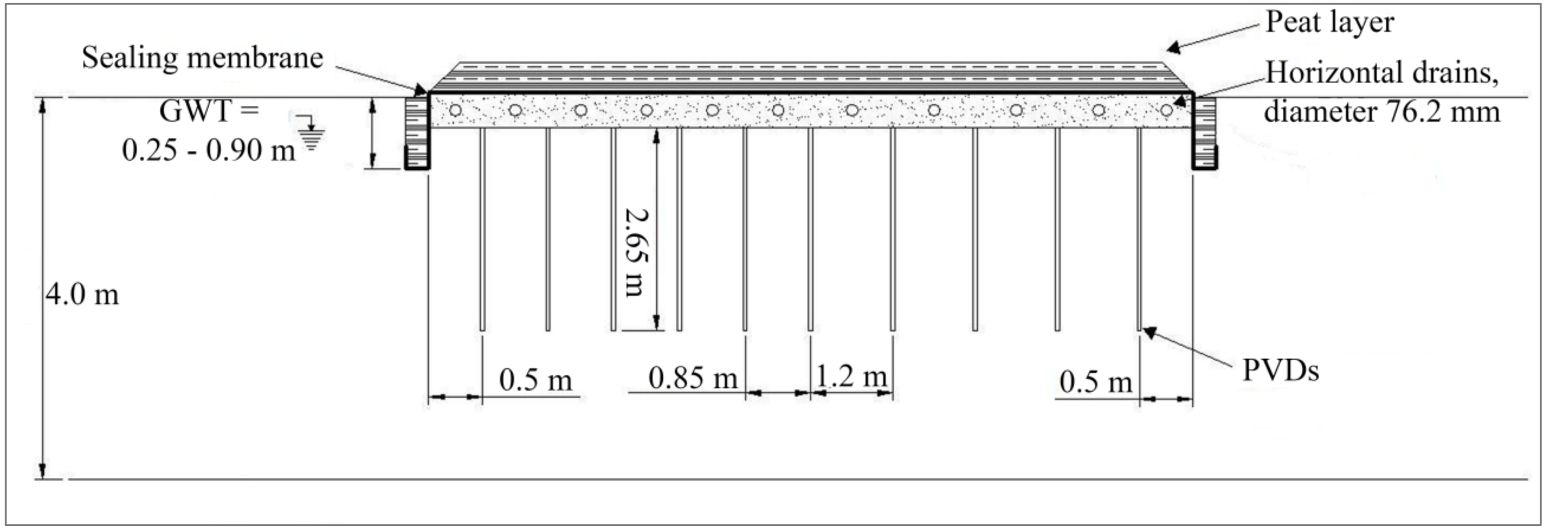
- Cyclic undrained triaxial-compression to investigate **cyclic behaviour of saturated loose sand–silt–GR mixtures**; **damping effect of GR improves liquefaction resistance**

  Ghadr S., Samadzadeh A., Bahadori H., O'Kelly B.C. and Assadi-Langroudi A., 2021, Liquefaction resistance of silty sand with ground rubber additive, *International Journal of Geomechanics (ASCE)* (In press)

PIs indicated with underlining

- **Vacuum consolidation**: 10 x 10m area field trial, 4m deep peat layer; demonstrate method in road construction (widening of existing roads) over peat deposits; 1.1-m settlement at end of 11 month pumping period (27.5% strain)

Vacuum lines, PVDs, instrumentation in place; awaiting sealing membrane cover.



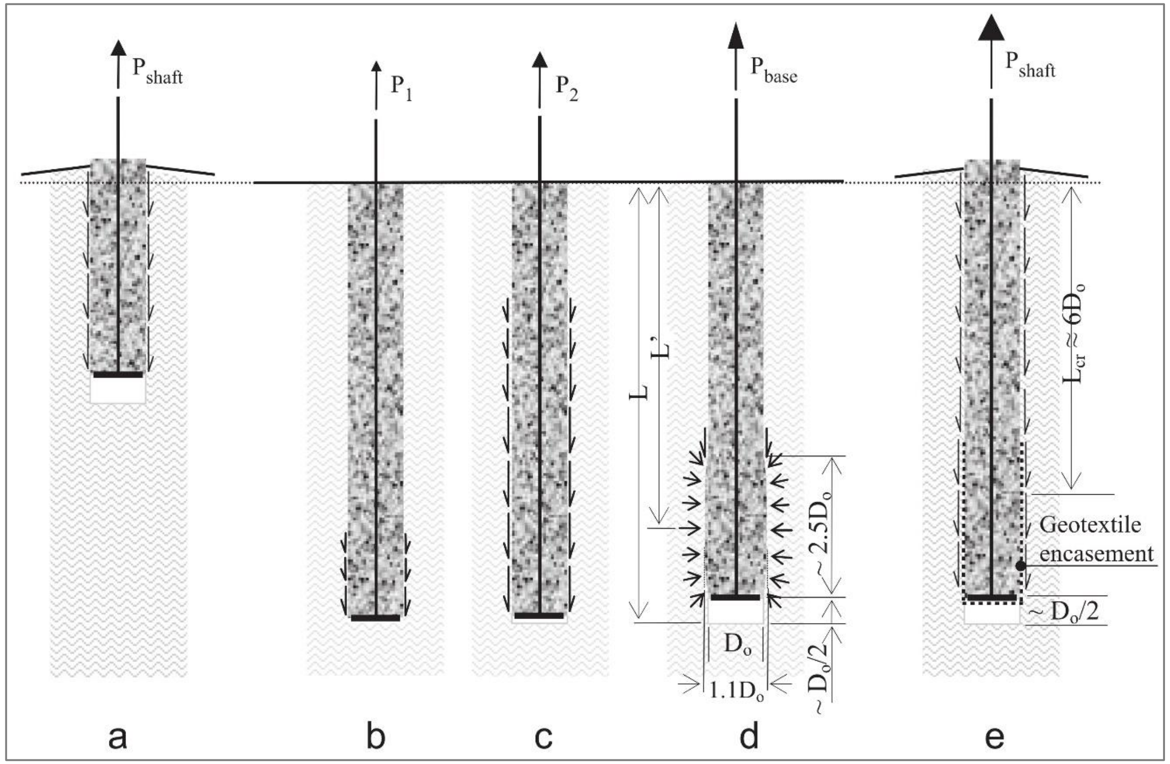
Cross-section of Ballydermot vacuum consolidation field trial

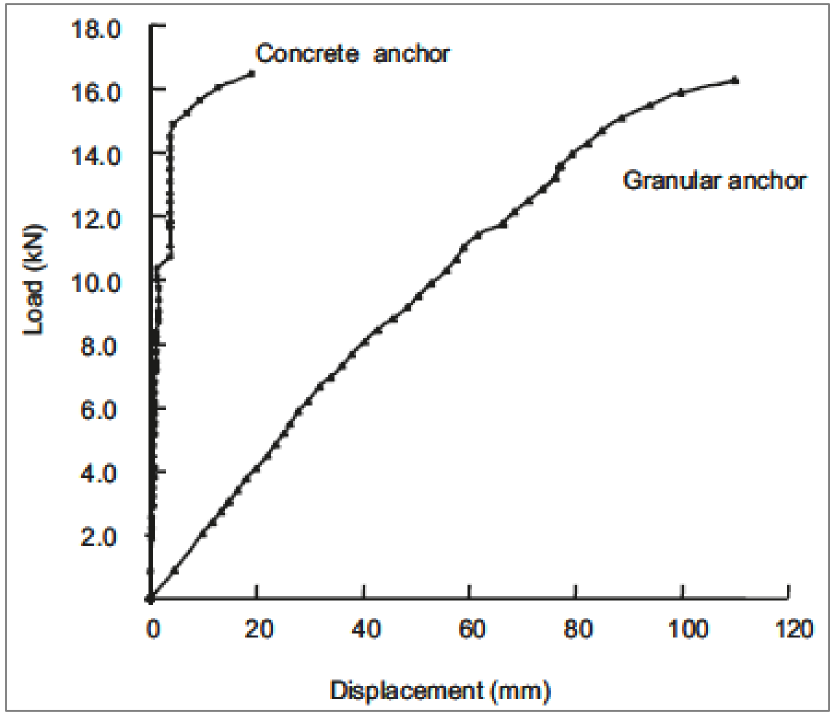
(O'Kelly B.C., 2015, Case studies of vacuum consolidation ground improvement in peat deposits. In, *Ground Improvement Case Histories* (Indraratna B., Chu J. and Rujikiatkamjorn C. (eds)). Kidlington, Oxford, UK: Butterworth-Heinemann (Elsevier), Ch. 11, pp. 315–345.)

With Drs. E.R. Farrell and J.P. Osorio-Salas

- **Granular anchors under pullout loading**

  (with Dr. V. Sivakumar, QUB)





0.07m dia. x 1.0m L anchors installed in made ground deposit ($s_u \approx 55$ kPa)

(a) shaft capacity failure (L < 6D); (b) small force resisted in shaft resistance over lower section of long column; (c) shaft resistance mobilizing upwards along column to resist increasing load; (d) failure in localized end bulging (L > 6D); (e) encasement of lower section of gravel column to impose failure in shaft capacity.

Sivakumar V., O'Kelly B.C., Madhav M.R., Moorhead C. and Rankin B., 2013, Granular anchors under vertical loading/axial pull, *Canadian Geotechnical Journal*, 50(2): 123–132.

O'Kelly B.C., Brinkgreve R.B.J. and Sivakumar V., 2014, Pullout resistance of granular anchors in clay for undrained condition, *Soils and Foundations*, 54(6): 1145–1158.

…. plenty of scope for research collaborations

Thank you for your attention!