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BISI Flood and Earthquake Hazard Mitigation Fraser River BC, CND

Yvo Veenis[1], Edward Kavazanjian Jr.[2], Leon van Paassen[3], Caitlyn Hall[4], Patrick Kwon[5], Caroline van de Steenoven[6], Ronny van der Heijden[6], and Eliam Vlijm[7]

[1] Manager Innovation, Groundwater Technology BV, Rotterdam, The Netherlands, E-mail: yvo.veenis@gtbv.nl
[2] Regents' Professor, Department of Civil, Environmental, and Sustainable Engineering, Arizona State University, Tempe, AZ 85287
[3] Design, Tender and Engineering Department, Boskalis, Rosmolenweg 4, 3356 Papendrecht, Netherlands, Email: leon.van.paassen@boskalis.com
[4] Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) and Biodesign Swette Center for Environmental Biotechnology (BSCEB), Arizona State University, Tempe, AZ.
[5] Graduate Research Assistant, Department of Civil, Environmental, and Sustainable Engineering, Arizona State University, Tempe, AZ 85287.
[6] Groundwater Technology BV, Rotterdam, The Netherlands
[7] Cohere Consultants BV, Amersfoort, The Netherlands

ABSTRACT

The Bio-Inspired Soil Improvement (BISI) process of microbially induced desaturation and precipitation (MIDP) offers the potential for reducing the risk of liquefaction and increasing resilience of the flood protection system along the lower Fraser River in British Columbia, Canada. Land in the lower Fraser River is susceptible to flooding during high water levels and dikes protect the hinterland from flooding. The dikes are constructed on river sediments that in some cases are susceptible to earthquake-induced liquefaction. Liquefaction of the sediments could lead to catastrophic failure of the flood protection system. Desaturation by in-situ microbial biogas production (the 'D' component of MIDP) can significantly enhance the seismic stability of the dikes as even a small fraction of gas has been shown to be sufficient to dampen pore pressure build-up under dynamic loading conditions and mitigate the triggering of liquefaction. Mineral precipitation of calcium carbonates, mostly as calcite, by in-situ microbial bio-cementation processes (the P component of MIDP) can mechanically strengthen sediment via inter-particle bonding and sediment particle surface roughening, improving sediment stiffness, strength, and dilatant behaviour. The use of these combined processes via MIDP to improve the seismic stability of the Fraser River dikes has been investigated using laboratory testing and numerical analysis. Based upon the results of the testing and analysis, a plan for a pilot test of the use of MIDP to mitigate the seismic risk to the Fraser River dikes has been developed.

INTRODUCTION

Implementation of Microbially Induced Desaturation and Precipitation (MIDP) to reduce the potential for earthquake induced liquefaction along the Lower Fraser River in British Columbia, Canada involves many uncertainties, including uncertainties regarding the MIDP process, the effect on geotechnical parameters, and the effect on soil stability. Therefore, a three step approach was employed using the Stage Gate decision model (AACE 1958) to decide on progressing to each next stage. The steps are:

1. Literature review (of the state-of-the-art scientific knowledge at that time, 2018);
2. Laboratory testing on samples of the liquefiable sediments of concern;
3. Field testing on an operational scale pilot project

The progress in technology development is monitored using the Technology Readiness Level (TRL) (EARTO 2014). At the time of start of this project in 2018, the technology was at TRL3 (experimental proof of concept); laboratory tests and work by others took development to TRL4: Technology validated in laboratory conditions. The field pilot will bring the technology to TRL6: Technology demonstrated in relevant environment.

LITERATURE REVIEW

A literature review was conducted in 2018 to evaluate the suitability of MIDP for the specific situation in the Lower Fraser River. Using a theoretical thermodynamic approach suggested by Kleerebezem and Heijnen (2010) and further elaborated by Pham et al, (2018) and Hall et at, (2023), the stoichiometry of the biochemical reactions in the MID(P) process could be determined. The metabolic conversion reaction consists of two parts: a catabolic reaction and anabolic reaction. The stoichiometry at maximum growth, is shown by Eq. 1:

$$1.21Ca_{0.5}C_2H_3O_2 + 0.97Ca_{0.5}NO_3 + 0.17H_2O \rightarrow CH_{1.8}O_{0.5}N_{0.2} + 0.39N_2 + 1.09CaCO_3 + 0.33H_2CO_3 + 0.74H_2O$$

Equation 1: Stoichiometric reaction at maximum growth Based on calcium acetate & calcium nitrate; note that all salts except calcium carbonate will be dissolved & dissociated in water.

Multiple factors affect the actual stoichiometry of the metabolic conversion, which varies between conditions of maximum growth and zero growth, depending on potential inhibition mechanisms. Consequently, the yield of nitrogen gas over nitrate (N_2/NO_3^-) ranges from 0.4 to 0.5. Understanding the actual growth rate is important, as it dictates the required resources to produce biogenic gas and $CaCO_3$ for adequate ground improvement. Equation 1 shows that the MID(P) reaction does not yield any by-products of major concern; H_2CO_3 will merge in the natural aqueous carbonate equilibria (from CO_3^{2-} to $CO_{2(g)}$). Besides providing a theoretical basis for the design of treatment solutions, the literature review indicated that based on the 'state of the art' at that time:

- At laboratory scale, MIDP can produce the bio-cementing calcite concurrently with a significant amount of biogas (primarily, N_2) without environmentally unacceptable by-products as long as sulphate is not present (Kavazanjian et al. 2015);
- A sufficient amount of gas can be produced in a single treatment within several days to significantly reduce the risk of liquefaction (O'Donnell et al. 2017);
- Published data from laboratory tests and field observations demonstrate that the produced gas can remain trapped in sediments for a prolonged period of time (Okamura and Soga 2006);
- Bio-cementation, considered a more durable sediment stabilization, requires multiple treatments over several weeks to months (O'Donnell et al., 2017);
- The processes that lead to sediment liquefaction are quantifiable and can be related to measurable sediment properties. Hence, it is possible to quantify the increase in resilience created by the MIDP process (van Paassen et al. 2017).

While the literature study showed the promise of the MIDP process, no field-proven cases had been performed at that time and the performance and effect of MIDP was expected to vary for different soil conditions. So, a thorough lab-scale testing program was required to draw substantiated conclusions on the applicability of MIDP for the Fraser River case. Since the literature study was completed, laboratory research for this project as well as other laboratory and field pilot projects have confirmed the original promise of mitigating earthquake induced liquefaction (Kavazanjian et al. 2015; Kwon et al. 2024; Moug et al. 2022; O'Donnell et al. 2017, Wang et al. 2021, van Paassen et al, 2017, Pham 2017). This emerging information was included in developing the detailed scope of the field pilot project.

LABORATORY TESTING

A laboratory test program was conducted on sediment samples of liquefiable soil from the Lower Fraser River region to evaluate the applicability of MIDP for the local sediment conditions. The main objectives for the laboratory test program were to answer the following questions:

- Can denitrifying bacteria grow in or be enriched from the sediments found at the proposed field pilot location?
- How much treatment is required to produce sufficient gas to avoid unacceptable pore pressure build-up during simulated earthquake shaking thereby mitigating the susceptibility for earthquake induced liquefaction?
- How much treatment is required to produce enough calcium carbonate to provide long-term mechanical strengthening of sediments and reduce the risk of failure for earthquake induced liquefaction?
- What factors may influence the process performance in the field? These factors include:
    - What is the effect of groundwater chemistry on the process performance?
    - How is the gas distributed in the sediment and how does it migrate?
    - How does produced biogas affect the substrate distribution in case of multiple treatments?

The laboratory test program (Wang et al, 2020; 2021b) demonstrated that:

1. Nitrate-reducing microorganisms can be enriched from the local sediments in the Lower Fraser River region and can be stimulated in-situ. Bio-augmentation with the a locally enriched microorganism culture can expedite initial denitrification activity;
2. By stimulating the MIDP process, enough desaturation can be obtained within a single treatment to significantly dampen pore pressure build up during cyclic loading. Without bio-augmentation the substrates are converted within a reaction period of one to two weeks. Once denitrifying bacteria are active substrates are converted within a 2 to 3 days.
3. Desaturation showed an increase in the cyclic resistance ratio (CRR) by a factor 1.3 to 2 (depending on the number of cycles, which correspond to representative earthquakes).
4. Cementation induced by the MIDP process also improves the cyclic shear resistance. Cyclic loading of a sample which was treated 6 times over a period of 3 weeks and resaturated after treatment to eliminate the effect of the gas showed a significant increase in number of cycles at a given CSR compared to the untreated sample. It is expected that the cementation provides a more durable strengthening than desaturation. However, the much higher amount of required substrates reduces the cost-effectiveness;

5. A combination of the two processes may provide promising results. It is expected that the combined effect of desaturation and cementation may increase the CRR further.

The laboratory results further showed that;

1. Desaturation also suppresses pore pressure build-up and increases the undrained strength and small strain stiffness of loose sands under monotonic loading;
2. Desaturation reduces the strength for dense, dilatant sands at large deformation strains because the gas also suppresses negative pore pressure build-up;
3. Groundwater chemical composition analysis indicated elevated values of electrical conductivity and ion concentrations in the targeted treatment zone between 10 and 15 m depth, as expected at the interface between marine and fresh groundwater conditions. This may influence the performance of MIDP in the field, but the effect is expected to be limited and can be accommodated at the concentrations detected;
4. For treatment in a naturally stratified sediment, it is expected that the gas will partly migrate laterally as well as upwards and get trapped underneath fine silt layers;
5. Gas retained in the sediment reduces the hydraulic conductivity;
6. The entrapped gas has a buoyancy force that opposes overburden pressure, resulting in a reduced effective stress.

The laboratory findings provided sufficient evidence to proceed to the next stages and prepare for a pilot field trial.

FIELD CONDITIONS

Figure 1. Municipal site for pilot

Pilot implementation was originally planned for 2020 but due to unforeseeable circumstances has been delayed to 2025. A location has been established for the pilot near the location where the samples for laboratory testing were taken. Figure 1 presents an aerial view of the pilot site and Figure 2 provides a cone penetrometer (CPT) profile taken close to the site.

The geology at the pilot location provides for a field demonstration of MIDP in two zones from 7 – 15 m below grade in naturally stratified sands. The blue bars in Figure 3 indicate the depths targeted for MIDP treatment. The shallower zone contains three sand layers, separated by layers of silty sand. The deeper layer consists of sand (only). The stratified structure is likely to retard vertical migration.

In the shallower zone, we expect the amendments to distribute predominantly in the sand layers and less in the silty sand layers. Initially, gas bubbles are expected to remain at the point of origin; if upward movement would occur, we expect the bubbles to remain trapped below the silty sand layer. We would monitor the sand layer at 7.5 m below ground to check for indications of gas bubbles migrating into this layer.

For the proposed treatment scheme, we require infiltration and extraction wells at three depths: 9-

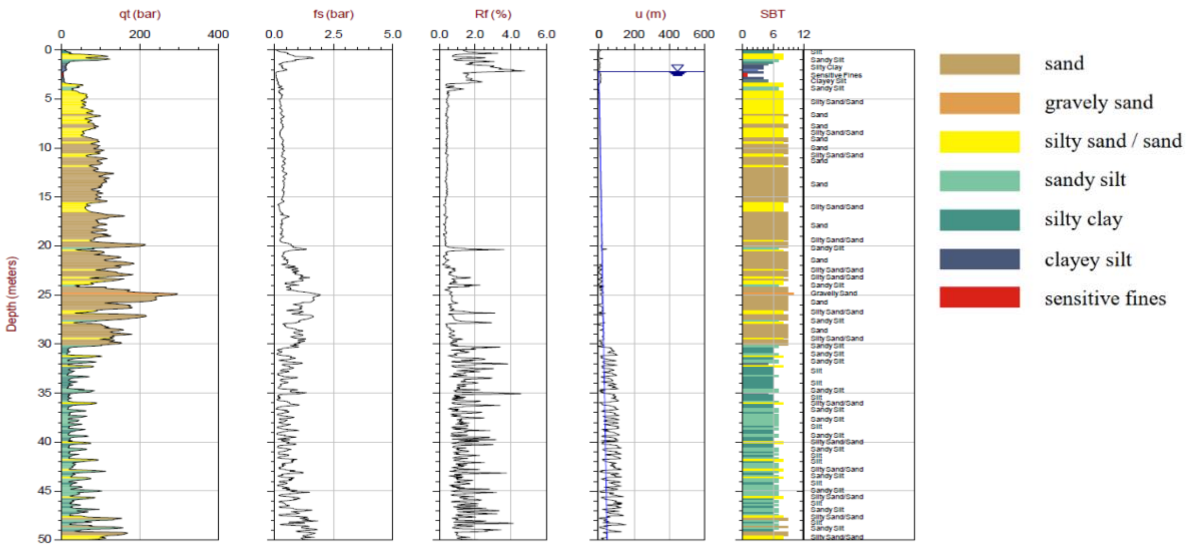

Figure 2. CPT in vicinity of new pilot location

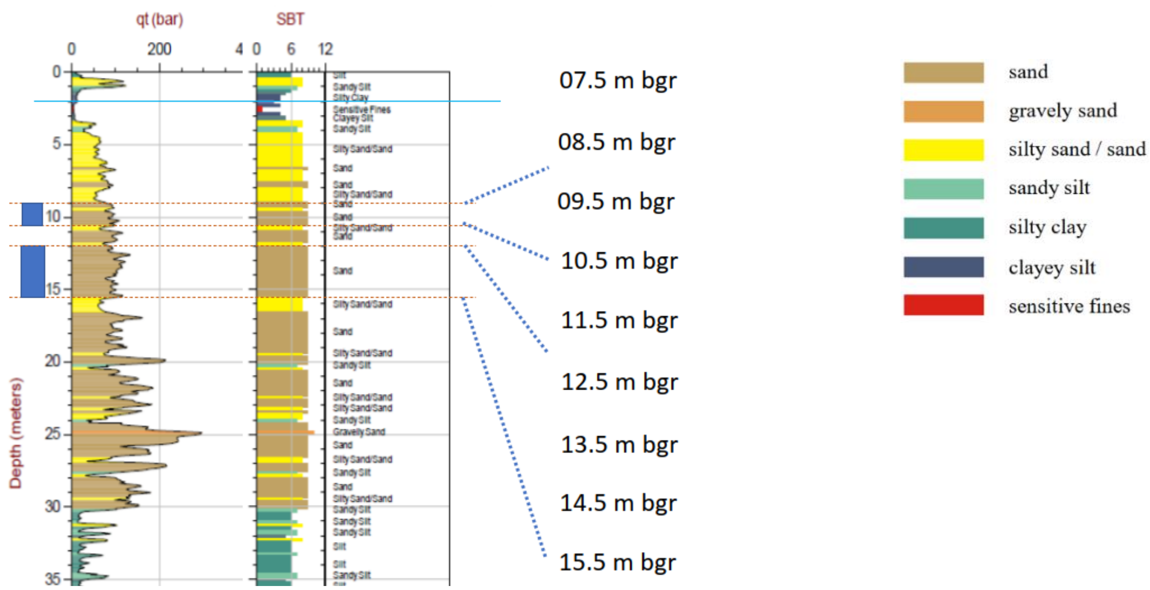

Figure 3. Depth ranges for MIDP Pilot

10.5 m below ground (mbg) for the shallower sand layers and 12 – 14 mbg and 14 – 15.5 mbg for the deeper sand layer. Monitoring wells will be installed at 2 depths: 9-10.5 mbg for the shallower sand layers and 12– 14 mbg for the deeper sand layer. In Situ sensors to record the level of (de)saturation will be installed at 4 depths: 7 mbg (in the sand above the shallow treatment zone); 10 mbg (in the shallow treatment zone; and 12 and 14 mbg (in the deeper sand layer). Two (2) PVC casings are to be installed for future cross-hole seismic test work in the pilot zone to 20 mbg.

Preparation for the pilot project also includes:

- One seismic CPT (SCTP) test to at least 35 m below grade close to (or at) the proposed MIDP pilot location (while CPT test holes can very well be plugged using bentonite, we would prefer to avoid any possible risk of introducing a 'vertical shortcut' for gas migration by off-setting the SCPT location, or by allowing ample time for the bentonite plug to seal).
- During the advancing of the SCPT, conduct the seismic tests at 2 m intervals from 4 – 16 m depth and at 5 m intervals to the maximum depth reached.
- Install at least one of the nests of monitoring wells proposed for the MIDP pilot and conduct a hydraulic conductivity tests (a slug test) on each screen.

The results of the SCPT and slug tests will be used to determine the exact (vertical) setting of each element of the proposed pilots and determine a 'base line' of geotechnical properties. The lay-out (in horizontal plane) of these probes and wells is shown in Figure 4. We assume that the grid-cell seize (the distance between the injection wells) will be 5 m. This will be finalized based on the results of the proposed permeability tests on monitoring wells. Table 1 provides the well and sensor specifications.

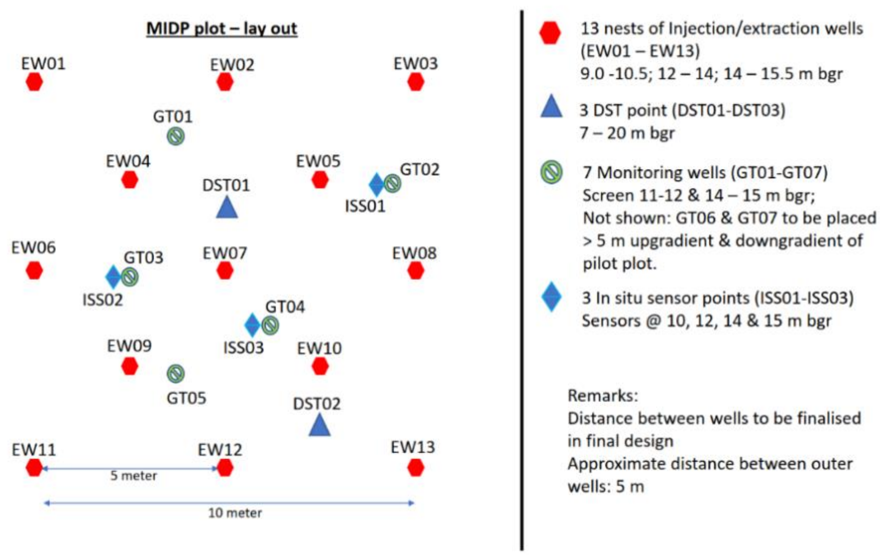

Figure 4. Proposed MIDP lay-out

Table 1. Well & sensor specifications

Type	#	diameter / type	Top of screen	Bottom of screen
Injection / extraction well	13 clusters of 3	50 mm HDPE, 0.3 mm slot	-09.00 -12.00 -14.00	-10.50 -14.00 -15.50
Monitoring well	3 clusters of 2	50 mm HDPE, 0.3 mm slot	-09.00 -13.00	-10.50 -14.50-
In-Situ sensor array	3 arrays of 4	-Teros 12 sensor	07.5, 12, 13.5 & 15 m	
sonic coring (20m) + PVC casing installation for future Downhole Seismic Testing (DST) work in pilot zone	3	50 mm PVC, not slotted (to be confirmed)	To 20 m	

IMPLEMENTATION

Implementation of the pilot test will consists of four phases:

1. Preparation & mobilisation
2. Application of amendments with associated monitoring to assure correct application
3. Short term monitoring of immediate and short-term effects
4. Long term monitoring (in particular to monitor longevity of the effects)

Preparation & mobilisation

In this phase, all materials and services will be procured. The specified SCPT tests and monitoring wells as well as slug tests on the monitoring wells will be implemented. Based on the results of permeability testing, the design of the pilot will be fine-tuned. The amendments will be stored in concentrations near the solubility limit concentration in separate suitable tanks to avoid premature bioreactions and chemical speciation.

Amendment injection

A fully automated extraction, mixing, and injection system will be deployed to the site. This is constructed in a standard 20-ft sea container, and consists of controls for the extraction pumps; flow meters; collection manifold; dosing system to add amendments on a volumetric controlled basis (a constant concentration of the correct molarity shall be injected); injection manifold; PLC-controls to steer the valve and collect essential data; remote controls. The unit will be connected to the internet via a GSM modem: allowing for control of the injection from the office.

Monitoring of the effects during injection

Groundwater will be extracted from wells at 2 $m^3 hr^{-1}$ and re-injected in two adjacent wells at 1 $m^3 hr^{-1}$ each. Table 2 summarizes the monitoring plan. The configuration of extraction and injection will be changed continuously, to obtain the best possible distribution of amendments. Then, amendments (appropriate for the pilot) from separate concentrated stock solutions will be added to the extracted groundwater and mixed. The water with amendments will be re-injected in the injection wells. Through an automated and remotely monitored process the infiltration rates (and pressures) can be monitored and set as required.

This treatment scheme is based on analysis by Kwon et al (2025), who modelled the expected amendment distribution using several patterns of wells. The results from these simulations, using

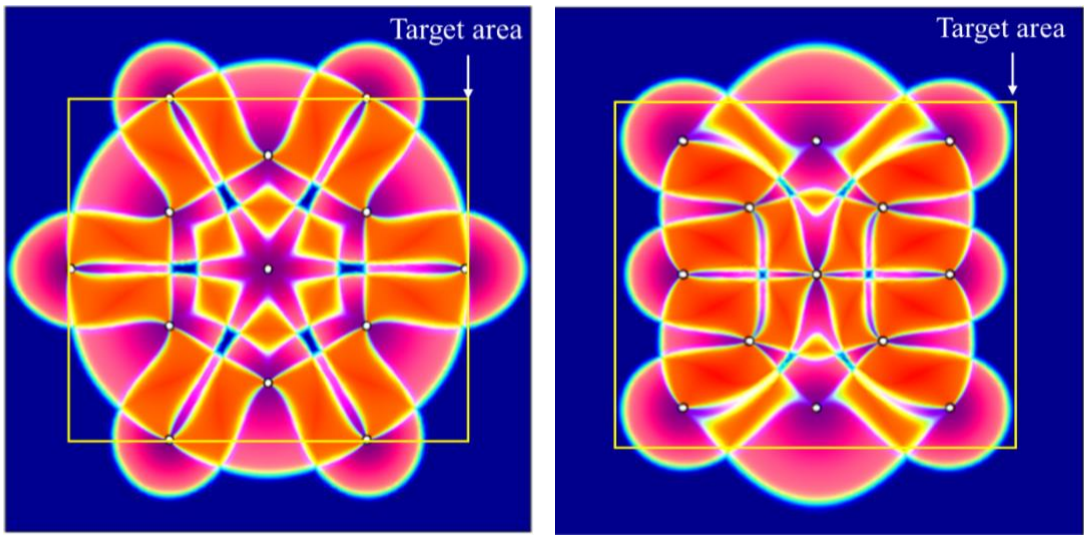

Figure 5. Simulation result of nitrate distribution with converted wells at 105 hours of injection (left) triangular pattern (right) rectangular pattern, including reversing the injection & extraction wells (from Kwon, 2014, reproduced with permission)

a triangular and rectangular grid flow patterns and including the effects of reversing flow directions in the injection and extraction wells, are presented in Figure 5. Care is taken to keep the water anoxic to reduce the risk of iron-oxidation and oxygen inhibition of denitrification. It is expected that 3 to 5 pore volumes of groundwater with amendments will be flushed through the system in 3 to 5 weeks. The number of flushes may be limited by the biogenic formation of gas, biomass and minerals that reduce hydraulic conductivity (Wang et al, 2023).

The electrical conductivity (EC) of the groundwater is directly related to the concentration of the amendment mixture, therefore, EC will be used as an analogue to monitor the process (Kwon et al, 2024). Both the transport and the consumption of substrates will affect the measured EC. At six points in the system (wells) we will install autonomous TEROS12 sensors (Metergroup) and dataloggers that frequently measure, store and, transmit the EC and volumetric moisture content of the soil. At regular time intervals, groundwater will be analysed to measure concentrations nitrate and calcium. The decrease of each of these is an indication of the efficacy of the nitrate reduction and calcite precipitation processes. The TEROS12 sensors that measure the EC are also able to measure the volumetric water content (VWR), which can be directly related to the degree of saturation. Based on the laboratory testing results, a single flush will likely reduce the degree of saturation by 20% (Pham et al, 2018, Kwon et al, 2024). Excess gas production beyond 20% produced in subsequent flushes is expected to spread laterally and vent upwards though the

extraction wells. Excess gas production beyond 20%, which is produced in subsequent flushes is expected to spread laterally and vent upwards though the extraction wells.
Several arrays of pore pressure sensors will be installed at different depth in the treatment zones. The pore pressure sensors will identify hydraulic pressure increase due to groundwater cycling and possible pressure build up as a result of gas production (Kwon et al, 2024. 2 PVC casings are to be installed for future Downhole Seismic Testing (DST) work in pilot zone to 20 mbg. In these casings, geophones can be installed to perform cross hole P-wave and S-wave measurement, which are indicative for desaturation and cementation respectively to 20 mbg.

Monitoring of the effects after injection

After injection, subsurface monitoring will continue. We will continue to measure all parameters at regular intervals, with particular focus on desaturation behaviour. We expect denitrification-

Table 2. Monitoring plan MIDP test

Process: MIDP				
Test	before	during	after	total
Seismic CPTu (Cone penetration test cone/sleeve/water pressure CPT test & seismic)	one in Pilot location tests to 35 m-grade (or refusal)	none	one in each pilot location	2
Groundwater injection & extraction well with soil & groundwater sampling & bore log	four in square and one in centre of square	n/a	n/a	13
Monitoring well with soil & groundwater sampling & bore log	7 nests of 2 wells	n/a	n/a	10
Soil sampling	n/a	n/a	5 locations to 15.5 m	5
Conductivity & temperature & pressure (water level)	Manual: daily C-diver in extracted water (continuous logging) C-diver in 1 mon well in each treatment cell	Manual: daily C-diver in extracted water (continuous logging) C-diver in 1 mon well in each treatment cell	Manual: once all wells C-diver in extracted water during post pilot treatment	
Concentration amendments Nitrate Reduction Calcium Acetate Calcium Nitrate	Field test in monitoring wells	Field test in extraction well: 3*/day Monitoring wells: daily 2 combined lab analyses / field test to calibrate field test to lab analytical	In injection and extraction wells: 2/ 1st week after completion	
Calcite analyses (field / CBBG Arizona, USA)	2 for each monitoring well (= 10)	none	4 near each monitoring well	20
Organic Carbon (soil)	one per cell			
Dissolved Organic Carbon (in water)	one from extraction well		one from extraction well	
gradation	one per soil layer encountered, based on UFC			
Shear strength	If possible, one on each test cell	none	2 per test cell, sampling from test pit	
(De)saturation: use GS3 probes, for desaturation. 1 or 2 sets of 3 GST's per cell., with cable & data logger. Includes EC measurements. 2 mon wells between injection & extraction well 6 sensors & data loggers. Sensors are lost. Data logger has Wi-Fi	Install 4 sets of four sensors. Record at intervals before injection	record continuously	record continuously	12
Seismic testing (in general, other than standardised seismic CPTu)	A pair of Down hole Seismic Testing points will be installed. In these pairs, seismic tests can be implemented at all desired depths.			2
Downhole Seismic Testing (DST)	Two locations, tests done before pilot, daily during pilot, quarterly after pilot			

induced desaturation to continue increasing until all nitrate from the substrates are converted to

N2 gas, biomass or CaCO3 minerals. Assuming that DST seismic test set-ups will be installed, seismic tests will be run during and after the pilots. When we expect sufficient calcite has been formed, CPT tests will be done (note that the first injection in the MIDP approach will unlikely produce sufficient calcite to result in changes in sediment properties that can be measured reliably in CPT tests). The specific locations will be selected later, such that they are near points where CPTs tests were performed prior to the pilot treatment. We will continue monitoring for 3 months. Recovering sediment samples to test for calcite precipitation is not expected to yield useful information.

Long-term monitoring

As the MIDP pilot aims for a combination of fast results though desaturation combined with slow results through cementation, we expect that, initially, cementation will be limited. Significant soil cementation is expected to be required before a significant increase in cone resistance during a CPT tests can be observed. In the case of desaturation only, cementation will be minimal, so no increase in cone resistance is expected (Moug et al, 2022) This means that a standard CPT is not an appropriate QA tool for desaturated soils unless sufficient cementation has taken place. In fact, it is expected (and observed in centrifuge testing of MIDP-treated soil by Hall et al. (2018)) that the cone resistance may reduce slightly due to desaturation, which may be attributed either to the buoyancy effect of entrapped gas or to the fact that gas phase also suppresses pore pressure build up during dilation which occurs at larger deformations. However, it is expected that such dilatancy and these large deformations would not occur prior to liquefaction triggering in sands that are relatively loose.

We identified three ways to assess the durability of the induced desaturation in the field:

1. by (semi) continuous monitoring of the Volumetric Water Content. VWC is directly related to degree of saturation and using can be measured using the same TEROS12 sensors, used to measure EC.
2. In the range of 100% to 95% saturation the bulk saturation may also be derived from pressure wave velocity measurements
3. Repetitive SCPT tests at the pilot locations.

Implementation and interpretation of these QA techniques will be performed in collaboration with subcontracted geophysical experts and universities. As long as we prove the soil remains desaturated we can posit, based on the results of the cyclic tests which were performed at a similar stress level as found in the field, the cyclic resistance has sufficiently increased.

CONCLUSIONS

Literature review and laboratory tests have demonstrated that the Bio-Inspired Soil Improvement (BISI) process of microbially induced desaturation and precipitation (MIDP) offers the potential for non-disruptively reducing the risk of earthquake-induced soil liquefaction in the lower Fraser River Basin. This would enhance the stability of the dikes are constructed on river sediments that in some cases are susceptible to earthquake-induced liquefaction. Liquefaction of these sediments could lead to catastrophic failure of the flood protection system. MIDP appears able to mitigate these seismic risks.

The process to take a highly promising technology as MIDP from scientific laboratory tests to field pilot demonstration under full operational conditions is complex and time consuming. In the case reported here this was further exacerbated by external factors, including the COVID pandemic. New scientific data that became available during the progressing stages of this project have been used to improve the design of the field pilot.

A detailed and carefully monitored and managed plan to take the MIDP technology from the Technology Readiness Level of 'scientific concept' to 'flight ready' is a prerequisite for practical application of this technology and is well-worth the effort in view of the major advantages that can be gained (reduction of costs, time & nuisance to implement as well as environmental impact) versus the level of confidence in reliability and longevity that geotechnical engineering requires.

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