

1 **Application of microbially induced calcite precipitation in erosion**
2 **mitigation and stabilization of sandy soil foreshore slopes: A**
3 **Preliminary Investigation**

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1 **Abstract**

2 Eroding foreshores endanger the floodplains of many estuaries, as such, effective and
3 environmentally friendly interventions are sought to stabilise slopes and mitigate erosion. As a
4 step in forestalling these losses, we developed laboratory microcosms to simulate tidal cycles
5 and examined the mechanisms of erosion and failure on sandy foreshore slopes. As an
6 experimental aim, we applied microbially induced calcite precipitation (MICP) to selected slopes
7 and compared the effectiveness of this microbial geo-technological strategy to mitigate erosion
8 and stabilise slopes.

9 To assess shoreline stability, thirty cycles of slowly simulated tidal currents were applied to a
10 sandy slope. Significant sediment detachment occurred as tides moved up the slope surface. For
11 steeper slopes, one tidal event was sufficient to cause collapse of the slopes to the soil's angle of
12 repose ($\sim 35^\circ$). Subsequent tidal cycles gradually eroded surface sediments further reducing slope
13 angle (on an average 0.2° per tidal event). These mechanisms were similar for all slopes
14 irrespective of initial slope inclination.

15 MICP was evaluated as a remedial measure by treating a steep slope of 53° and an erosion-prone
16 slope angle of 35° with *Sporosarcina pasteurii* and cementation solution (0.7 M CaCl_2 and urea)
17 before tidal simulations. MICP produced 120 kg calcite per m^3 of soil, filling 9.9% of pore
18 space. Cemented sand withstood up to 470 kPa unconfined compressive stress and showed
19 significantly improved slope stability; both slopes showed negligible sediment erosion. With
20 efforts towards optimisation for upscaling and further environmental considerations (including
21 effect of slope saturation on MICP treatment, saline water and estuarine/coastal ecology amongst
22 others), the MICP process demonstrates promise to protect foreshore slope sites.

23 **Keywords:** MICP, slope stabilization, erosion mitigation, foreshore, rip current.

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1 **Highlights**

- 2 • Untreated and treated sandy slopes were subjected to tidal currents in a microcosm
- 3 • Untreated slopes fell to angle of repose, eroding 0.2° slope angle per tidal event
- 4 • MICP treatment was with *S. pasteurii* and solutions of urea and calcium;
- 5 • Significant cementation was achieved with calcite filling 9.9% pore space.
- 6 • MICP-treatment stabilised slopes resulting in negligible erosion.

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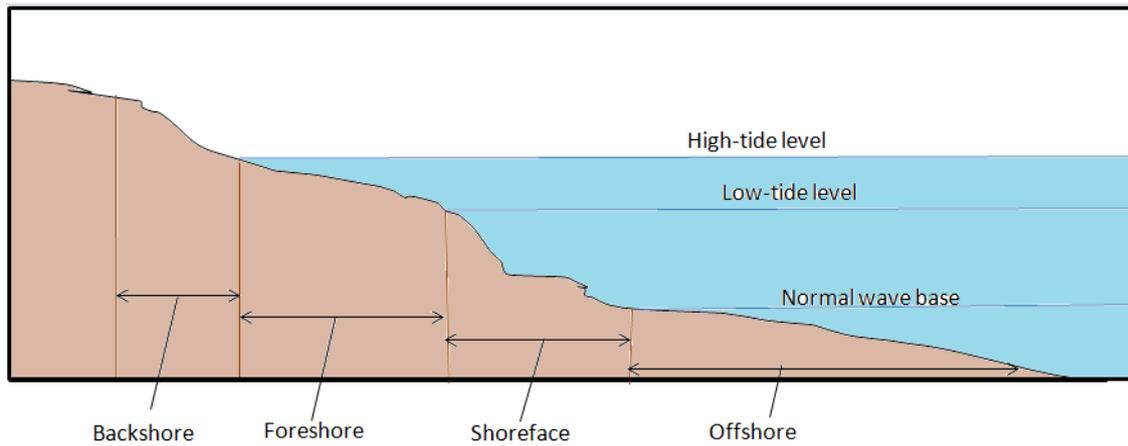
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1 **1.0 Introduction**

2 The erosion of foreshore slopes by rip currents and associated tidal flows represents a major
3 problem in many estuarine environments (Short, 1985; Winn et al., 2003). For example, erosion
4 threatens the bank defences that protect >90,000 ha of arable land and 30,000 people with
5 property within the flood plain of the Humber estuary in the UK (Winn et al. 2003). Another
6 possible implication of the foreshore erosion is the loss of intertidal habitat due to the
7 phenomenon of 'coastal squeeze' or decrease in spatial extent of intertidal areas over time (Fujii
8 and Raffaelli, 2008).

9 Typical rip current events take place for less than 20 seconds at 3 - 4 hours intervals, with
10 velocities of up to $1 \text{ m}\cdot\text{s}^{-1}$ (Short and Brander, 1999; MacMahan et al., 2006; Scot et al., 2009;
11 Haller et al., 2014). Consequential slope failure and erosion from these tidal currents remain a
12 geotechnical challenge in most coastal and estuarine environments. Foreshores (see Fig.1),
13 whether coastal or estuarine, are gradually washed away as they undergo erosion mechanisms
14 due to constant exposure to tidal currents. Mechanisms of coastal and/or estuarine foreshore
15 erosion under tidal currents have not been fully elucidated in literature. Even though coastal
16 shorelines differ from estuarine environments in terms of geology and intensity of tidal events
17 experienced (Sharples, 2006), it may be worthwhile to borrow the already established concept of
18 erosion mechanisms on coastal shoreface as a starting point to hypothesize if expectedly similar
19 erosion mechanisms may occur on estuarine foreshores. Erosion on coastal shoreface involves
20 gradual detachment and transport of soil grains down the slope surface during the up-rush phase
21 of tidal currents; it is then deposited on the slope surface or foot of the slope upon tidal back-
22 wash. Some sediment may be transported away from the area of detachment. Depending on the
23 velocity of the tidal currents and the ease of detachment of soil grains, erosion can occur quickly
24 and consequentially leads to loss of entire shores and increased incidences of flood in coastal
25 flood plains (Conley and Inman, 1994; Cox et al., 1998; Petti and Longo, 2001; Elfrink and
26 Baldock, 2002; Longo et al., 2002; Cowen et al., 2003; Conley and Griffin, 2004; Masselink et
27 al., 2005).

1 Studies reported in the literature have identified soil properties such as clay content, microbial
2 activity, bulk density and moisture content as factors that affect coastal or hillslope erosion
3 (Amos et al. 1996; Fang and Wang, 2000; Fang et al., 2013); by extension, it would be
4 reasonable to add that these factors and others like shore slope angles, tidal effects and nature of
5 available vegetative cover may also play key roles in estuarine foreshore erosion.



6

7 **Fig.1: Typical coastal/estuary anatomy showing foreshore, tide levels and other shores**

8 Considering the above erosion mechanisms and factors that interplay in shore erosion, it
9 therefore follows that a potential strategy to effectively control estuarine foreshore erosion would
10 be one that is designed around these factors and supposed erosion mechanisms. Effective
11 stabilisation technique for foreshore slopes remains a challenge, and there are no approaches
12 proposed in existing literature to prevent foreshore erosion with minimal implications. If one
13 were to think about remedial measures for foreshore slope erosion, one may approach these by
14 borrowing techniques that are currently adopted in general erosion control strategies; these may
15 be by applying techniques that support the slopes in any of the following two ways: 1) by using
16 foreign soil improvement material, e.g., use of membrane structures for soil reinforcement (Liu
17 and Li, 2003), chemical cementation using cement, fly ash, lime or inorganic polymer stabilizers
18 (Liu et al., 2011); or 2) by simply improving the *in-situ* soil properties through the application of
19 the 'biogenic/microbial methods' (Agassi and Ben, 1992; Dejong et al., 2013). However, there
20 are limitations to some of these techniques.

1 Foreign materials like geotextiles, wire meshes, cable nets, nails or sheets and other membrane
2 structures physically installed to promote slope enforcement do not modify soil properties
3 (Singh, 2010); they are often expensive and require machinery that may disturb infrastructure
4 (van Paassen et al., 2009); and they also affect plant growth. Chemical/organic stabilizing agents,
5 apart from being ecologically unfriendly in some cases, may fail when applied to soils subject to
6 constant wet conditions such as coastal shores; there is also the challenge of stabilizers having
7 high viscosity or hardening too fast, and therefore being unsuitable for application in large areas
8 (van Paassen et al., 2009).

9 Based on these submissions, therefore, a more formidable remedial technique suitable for
10 estuarine foreshore slope erosion might be the biogenic/microbial approach for soil property
11 improvement. This is the premise, on which the current trend of microbial geotechnology to
12 improve soil properties, has developed. This technology has shown superlative efficiency and
13 effectiveness in improving soil properties with ease and less cost, and it enhances environmental
14 sustainability (Dejong et al., 2013).

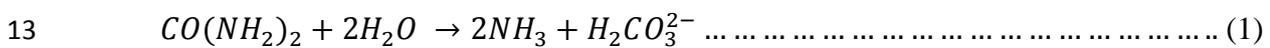
15 One type of microbial geotechnology based technique adapted for soil stabilization is
16 microbially induced calcite precipitation (MICP), where microorganisms of the *Bacillus* genus
17 (e.g., alkaliphilic *Sporosarcina pasteurii*) induce calcite precipitation through the hydrolysis of
18 urea in the presence of dissolved calcium salt solution, organic carbon and optimum
19 environmental conditions (pH 7-9, temperature 27-30°C) (Mitchell & Santamarina 2005; Van
20 Paassen et al. 2007; Whiffin et al., 2007; Harkes et al., 2008; Ivanov and Chu, 2008; van Paassen
21 et al., 2009; DeJong et al., 2009).

22 The application of the MICP techniques for stabilizing foreshore slopes still remains a budding
23 line of research. Meanwhile, laboratory investigations to understand soil erosion processes have
24 been reported in the literature, but little has been done regarding coastal foreshore slopes. The
25 closest investigations, linking laboratory studies of water-induced soil erosion and/or
26 stabilization to MICP treatment, were done by Van Paassen et al. (2010) and Esnault-Filet et al.

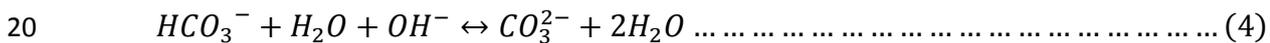
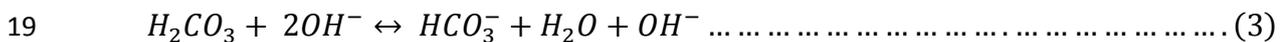
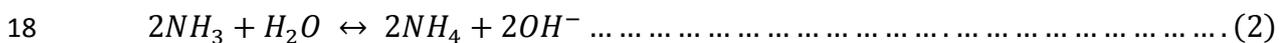
1 (2012). Even though their work involved treatment of saturated soils, it did not consider soils at
 2 slopes, their erosion mechanism, nor the effects of intermittent tidal currents on soil slopes. Here,
 3 the experimental laboratory-scale microcosms aim to demonstrate slope failure and erosion
 4 mechanisms on soil slopes as tidal processes occur and to test the potential effectiveness of
 5 MICP in stabilizing such slopes and mitigating slope surface erosion. This microcosm approach
 6 is an advantageous preliminary step, which provides an experimental approach at laboratory
 7 scale, where environmental factors can be controlled, and scaled down models of actual soil
 8 slopes could be investigated. Subsequently, other complex variables may be introduced as a
 9 build-up towards large-scale field implementation of findings.

10 **1.1 Background**

11 MICP biochemistry is well documented in literature (Ferris et al., 1996; Mitchell et al., 2010). It
 12 involves urea hydrolysis:



14 Ammonia in the presence of water forms ammonium and hydroxyl ions, which increases
 15 ambient pH around the bacterial environment to about 9 (equation (2)) (Dejong et al., 2006; Van
 16 Paasen, 2009), and the resultant alkaline environment shifts the carbonate systems to ultimately
 17 producing more carbonate ions (equations (3-4)):



21 The carbonate reacts with calcium ions, forming calcium carbonate, or calcite crystals, as
 22 follows:



1 Calcite crystals serve as the 'cementing bridges,' which bind soil grains together, and they have
2 been found to be highly effective in binding soil particles up to 50 years and improving their
3 geotechnical properties, such as shear strength (DeJong et al., 2009). Cementation, whether
4 obtained from bio-cementation or bio-clogging, depend on several factors, such as: 1) bacterial
5 aggregation (El Mountassir et al., 2014); 2) the composition and concentration of soluble
6 calcium (Harkes et al., 2010); 3) pore size distribution of the media; 4) application strategy of
7 bacteria (e.g. one pore volume) and salt (e.g. two pore volumes) to promote fixation,
8 homogeneous distribution of bacteria and cementation yields (Harkes et al., 2010); 5) the
9 injection rate into the soils (depending on the permeability of soil media); 6) the grouting
10 technique and the duration at which specified volume is applied.

11 **2.0 Material and methods**

12 **2.1 Materials**

13 **2.1.1 Microbial suspensions**

14 Solutions of *S. pasteurii* were prepared from strain *ATCC 11859*, which have been stored in agar
15 plates (comprised of Brain Heart Infusion (BHI) agar and 2% urea; see Table S2 for media
16 composition), and grown overnight (BHI broth and 2% urea). Cells were harvested at late
17 exponential phase, centrifuged (10 000 x g, 10 min) and diluted to final OD₆₀₀ of 1.0 (equivalent
18 to 3 x 10⁸ colony forming units (CFU) mL⁻¹ (El Mountassir et al., 2014)) at one pore volume to
19 be treated. In both treatment cases, the BHI media were prepared with deionized water and
20 autoclaved at 121°C for 20 minutes. Urea solutions were sterilely filtered (0.2 µm filter) into the
21 broth. Media and inoculants were placed on a shaker table at 160 rpm for 24 hours during
22 growth.

1 **2.1.2 Cementation solution**

2 A solution of 0.7 M CaCl₂ and urea served as fixation fluid and cementation fluid. This molar
3 concentration was based on the recommendation of Harkes, et al. (2010) that solutions greater
4 than 0.5 M CaCl₂ and urea are best suitable for cementation.

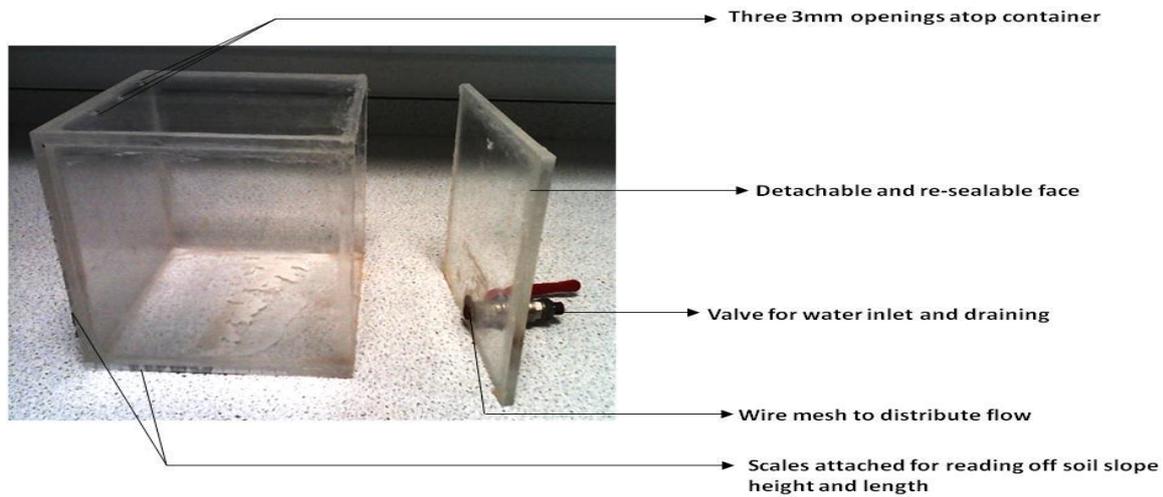
5 **2.1.3 Perspex container**

6 The process of simulating tidal cycles for determining soil slope erosion and the injection of
7 treatment solutions into soil slopes were all carried out in a cube-shaped container (0.2m sides)
8 made from 'Perspex' (polymethyl methacrylate, PMMA). PMMA is a tough, transparent,
9 synthetic fibre plastic that serves as a good alternative for glass for applications in environmental
10 and life science laboratory experiments (Uzunoglu et al., 2014) (see Figure 2). Silicone sealant
11 was used to bind and seal the edges. One face was detached by simply using a sharp scalpel to
12 separate the joints (this side was re-sealed with silicone sealant after soil was supplied into the
13 box). This side of the container is fitted with a valve in the outward end and a wire mesh to
14 distribute flow in its inward area. A pipe of 4 mm internal diameter was used to supply and
15 drain water via the dual inlet-outlet valve. The water tank was positioned at height of 1.3 m
16 above the base of the Perspex box. Three holes measuring 3 mm ϕ were made at the top of the
17 container to help transfer air during the tidal cycles and, secondly, serve as ports for flexible
18 plastic tubing during injection of treatment solution.

19 **2.1.4 Soil**

20 Sandy soil was sourced from Troon beach in Ayrshire, UK and air dried in the laboratory.
21 Intrinsic and experimental test properties of the soil are given in Table 1 and Table 2,
22 respectively, while the grain size distribution of the soil is shown in Figure S1 (supplemental
23 figure).

24



1

2 **Figure 2: The Perspex box container.** Cube shaped with each side equal to 200 mm.

3 **Table 1: Intrinsic properties of the sandy soil.**

Property	Value	Determination method
Saturated hydraulic conductivity, cm/sec	1.5×10^{-3}	Constant head method
Specific gravity	2.65	
Coarse sand percentage, %	0.6	
Medium sand percentage, %	31.9	
Fine sand percentage, %	67.5	ASTM D422-63e2 Standard
D ₆₀ , mm	0.4	methods for particle size
D ₃₀ , mm	0.3	analysis of soils
Effective size (D ₁₀), mm	0.24	
Coefficient of curvature (C _c)	0.94	
Coefficient of uniformity (C _u)	1.67	
Classification	Uniformly graded sand	ASTM D2487-06e1 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
Angle of repose (oven-dried sample)	28.5	Miura et al., 1997
Angle of repose (wet)	35.7	

4

1 **Table 2: Properties of the packed soil in the experiments.**

Property	Value	Remarks
Bulk density (g cm ⁻³)	1.82 - 1.89	This was achieved by pouring the required quantities of water and soil at specified moisture content into the Perspex box via the detachable face, and literally 'compacting' the wet sand using hands and spatula to fit into the slope expected, guided by the scale attached to the Perspex box.
Dry density (g cm ⁻³)	1.47 - 1.50	
Porosity	0.44	
Initial Moisture content (%)	25.0	This moisture content was found sufficient to wet soil completely as if due to tidal effect, and also enough to prevent slope from collapsing by itself.
Slope angles (°)	35, 48, 51, 53	35° is the approx angle of repose for the wet sand; 53° was the steepest stable slope obtainable by compacting soil at 25 % moisture content for the experimental purposes

2

3 Soil samples were oven-dried at 105°C overnight to minimise interferences from antecedent

4 microbial or plant communities. Quantity of soil needed and soil pore volumes were determined

5 from the slope dimensions and bulk density. Computed pore volumes were used for determining

6 volumes of bacterial and cementation solutions.

7 **2.1.5 Water**

8 To minimise any interplay of extraneous variables like salt concentrations in water and/or

9 introduction of foreign bacteria species, water was purified by reverse osmosis. Also, the same

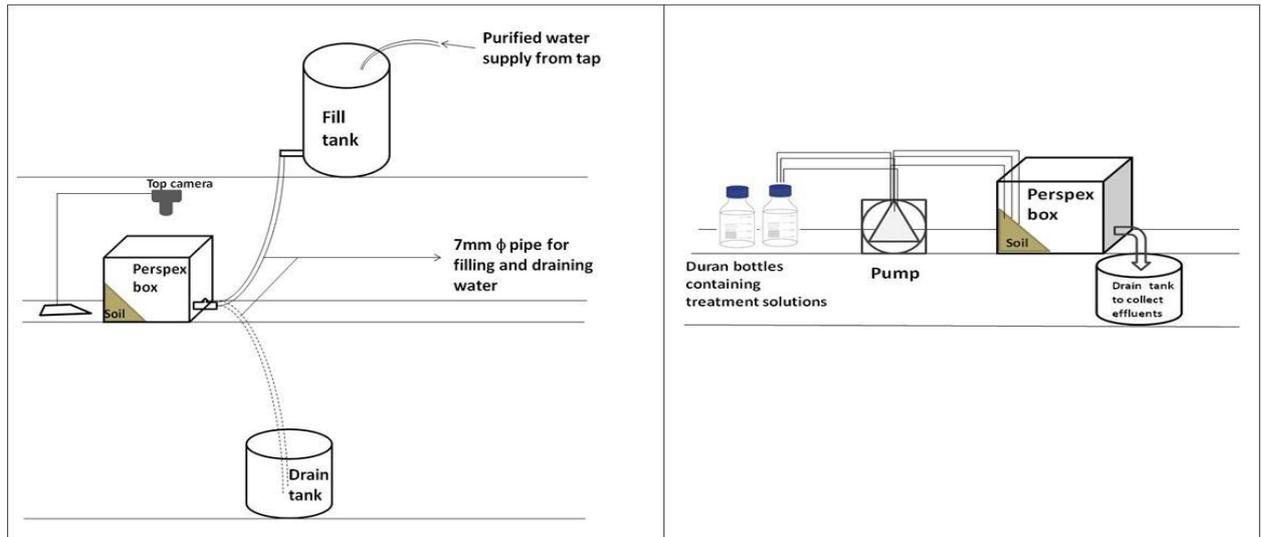
10 purified water was used at intervals between application of bacterial solution and cementation

11 fluids to avoid clogging.

1 2.2 Experimental set up/methodology

2 Two basic experimental set ups were developed for each assay. A schematic view of the first set
3 up, which established the slope erosion mechanisms, is shown in Fig. 3a. The second set up,
4 which was for the MICP treatment process, is as shown in Fig. 3b.

5



6 Figure 3. (a) Experimental set up for simulating the tidal current processes to determine slope erosion/failure mechanisms.

(b) Experimental set up showing the MICP treatment process with permeation grouting. Flexible tubes were used to transfer treatment solutions via a pump into the soil. Effluents that flowed out were collected as shown.

7 The investigation involved two core workplans to achieve experimental objectives, these are: 1)
8 simulation of tidal cycles without any cementation treatments, performed to establish baseline
9 erosion mechanisms with three different slope conditions, i.e., 48° , 51° and 53° ; and 2)
10 simulation of tidal cycles on MICP-treated slopes. The microbial and cementation solutions
11 necessary for slope treatments were prepared for two slope treatments: one for the steepest slope
12 before collapse (53° , which is steeper than the angle of repose) and the second, representing the
13 approximate slope formed immediately after steep slope collapsed (35° , erosion prone slope); it
14 was after the collapse to this slope that progressive sediment erosion trends were observed and
15 studied per tidal cycle. Other additional experimental procedures for determination of calcite

1 production and estimation of strength of cemented soil were, thereafter, carried out to determine
2 treatment effectiveness. Specific details for each work plan are presented below.

3 **2.2.1 Simulation of tidal cycles (on untreated and treated soils).** Initial microcosm
4 simulations established and evaluated slope failure at three different starting slopes (48°, 51°,
5 and 53°). The prepared sand (section 2.1.4) was brought to a moisture content of 25.05% and
6 formed into slopes at compacted bulk density of 1.82 -1.89 g/cm³ in the Perspex container. After
7 MICP treatment on two selected slopes (53°and 35°), another set of tidal simulations was
8 performed to evaluate the effect of treatment on slope failure. Two cameras (Nikon 360XLR
9 and a webcam) were fitted on retort stands from the top and side of the box to monitor bank
10 stability; video and still images were captured using 'Candy Labs VideoVelocity' software. The
11 procedures for both tidal simulations (on the untreated and treated soil slopes) were same and
12 carried out in the Perspex box as follows:

13 The uprush water flow came in at inflow rate of 10⁻⁵ m³/s. The rising tide was allowed to fully
14 saturate the slope with the water level submerging the slope crest by 0.08 m. As soon as the
15 uprush got to the top of the slope, the valve was opened to allow the tide fall by draining water
16 out of the Perspex box at 1.3 x 10⁻⁵ m³/s. Backwash velocity was slightly higher than uprush
17 because the slope head makes the rip current backwash faster than its upflow. Following the tidal
18 cycle, the change in slope was noted by measuring the height and base of the soil slope in the
19 Perspex box using the graduated scale attached to it. Sediments washing into the drain container
20 were also collected, weighed and recorded at the end of every ten cycles. The mass of soil
21 deposited at foot of slope was determined at the end of the thirtieth cycle. The tidal procedure
22 was repeated thirty times and carried out for soil masses of 2250g, 1000g and 500g, forming
23 slope angles of 48°, 51° and 53° respectively, as well as for the treated slopes of 53°and 35°.
24 (The soil masses adopted were scaled down progressively to determine erosion mechanism at
25 various soil quantities and to have minimum possible soil volume that effectively demonstrates
26 erosion mechanisms and minimise the resources required for MICP).

1 **2.2.2 Application and assessment of MICP technique.** The procedures involved in injecting
 2 the microbial suspensions and cementation solutions (sections 2.1.1 and 2.1.2) into pre-selected
 3 sandy slopes (53° and 35°), and some complementary tests or ancillary investigations carried out
 4 to assess/quantify effectiveness of treatment and quality of cementation on the two treated soil
 5 slopes are detailed as follows:

6 ***Injection of bacterial solution and cementation solution into the soil.*** Air dried soil samples
 7 were collected, autoclaved and weighed. The soil mass used, moisture content and compacted
 8 bulk density for both slopes treated are given in Table 3.

9 **Table 3 : Masses, moisture content, volumes and bulk densities of treated slopes**

Slope angle treated	Slope dimension (cm) and ratio	Mass of autoclaved soil (g)	Moisture content (%)	Volume of soil (cm ³)	Compacted bulk density (g/cm ³)
35°	4.8/6.9 (1:1.44)	500	25.05	331.2	1.89
53°	8/6 (1:0.75)	700	25.05	480.0	1.82

10
 11 After compacting the soil to desired bulk density in the Perspex box, three grout pipes (flexible
 12 plastic straws) were used per slope treatment to disperse cementation solutions. The length of the
 13 straws was randomly perforated using a pin, and the bottom of each straw was plugged with
 14 silicone sealant. These were then installed through the openings atop the Perspex box into the
 15 soil. The peristaltic pump was calibrated to apply the solutions at 6 mL/min, as advised by
 16 Whiffin et al. (2007). To induce calcite precipitation by grouting, the pores of sandy soil slopes
 17 were treated by application of one pore volume of *S. pasteurii* suspension and two pore volumes
 18 of 0.7 M CaCl₂ and urea (fixation/cementation) solution, sequentially. The bacteria solution was
 19 first pumped in, and thereafter, the conduits (tubes) were flushed with de-ionized water for about
 20 5 minutes to avoid clogging. After this interval, the cementation solution was then injected into
 21 the soil. This entire process represents one treatment cycle. Multiple injection of bacterial

1 solution is adopted here as recommended by El Mountassir et al. (2014) to forestall the
2 possibility of microbial incapacitation due to encasement in calcite as reported by Cuthbert et al.
3 (2012) and Tobler et al. (2012). Based on pore volumes, 150mL and 220mL suspension solutions
4 of *S. pasteurii* were applied to soil slopes of 35° and 53°, respectively. *S. pasteurii* strain ATCC
5 1187 were aseptically cultured on BHI (Table S.1 for media composition) agar plates with 2%
6 w/v urea for one week at 21°C, and then stored at 4°C for short-term storage. To prepare
7 solutions for each treatment cycle, the microorganisms were harvested from the plates and
8 aseptically inoculated into BHI broth with 2% urea at pH of 7.4 (based on El Mountassir, et al.
9 2014). Fresh solutions were prepared daily.

10 Eighteen cycles of MICP treatment solutions (3 times per day, for 6 days) were pumped via
11 tubing to soil slopes (35° and 53°). One-hour interval was allowed in between treatment cycles to
12 enable the reactions to completely take place in the soil before another cycle begins. The
13 adoption of eighteen treatment cycles over six days was based oral communication with El-
14 Mountassir and McLachlan (2014).

15 ***Effectiveness of treatment on slope stability and erosion mitigation.*** MICP-treatment efficacy
16 was tested by subjecting slopes to simulated tidal currents. At the end of the eighteen treatment
17 cycles, thirty tidal current cycles were simulated on each of the two treated slopes (Section
18 2.2.1); slope changes were noted, to compare with changes in untreated slopes subjected to same
19 tidal events.

20 ***Determination of amount of calcite production.*** Effluent solution were collected from the foot
21 of the soil slope with a 20-mL syringe during the treatment cycles, and filtered through a 0.42-
22 µm sterile filter to remove bacteria. Sample collections were done at exactly five minutes after
23 the 4th, 7th, 9th, 11th and 13th treatment cycles, and were frozen in plastic centrifuge tubes at -
24 20°C. This entire sampling process was conducted within 1-2 minutes to minimise post-sampling
25 and pre-storage chemical reactions.

26 Effluent ammonium and calcium concentrations were determined using colorimetric KONE
27 analyser and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES),

1 respectively, at the Strathclyde Eco-Innovation Unit (SEIU) at University of Strathclyde.
2 Samples were diluted 1:200 mL and 1:500 mL, respectively, for detection limits. Ammonia
3 represented reaction by-products, while the calcium concentrations represented unreacted
4 reagent precursor.

5 Additionally at conclusion of MICP treatment and tidal cycles, the cemented soil slopes were
6 removed from the Perspex box and oven dried; the oven dried mass was determined using the
7 weighing scale, and then the sample was washed in 10% HCl to remove the calcite formed. The
8 respective sample weights after acid washing and oven drying were recorded.

9 *Estimation of effectiveness of the treatments versus amount of calcite formed.* Strength of
10 cemented soil was determined using unconfined compressive strength (triaxial) test machine
11 (Wykeham Farrance, Trittech Model, 50kN capacity). Four core samples (two from the 53° slope
12 and two from 35° slope) were collected and trimmed to frictionless smooth edges of
13 height:diameter ratio of 1.2:1. The length and diameter of specimens to be tested were measured
14 and recorded, and as much as possible, moisture loss was minimised in each specimen. Without
15 applying confinement, the triaxial cell was placed on the sample. According to ASTM D2166-00
16 standards, rate of strain was computed at 1.27 mm min⁻¹. The test started by application of load
17 and stopped when a drop in the stress-strain plot was observed.

18 **3.0 Results and Discussion**

19 **3.1 Examination of slope stability - *Experiments on untreated sand slopes:*** Thirty tidal
20 cycles were simulated on three different slopes initially to establish slope failure and understand
21 erosion mechanisms. Figure 4 shows the response or evolution of the slope for the three different
22 initial inclinations of the slope during the first simulated tidal cycle.

23 Visual evidence showed that the first simulated rip current cycle caused a drastic collapse of the
24 untreated slope in all three cases (48°, 51° and 53°); subsequently, gradual sediment erosion

1 continued, with slopes changing progressively from about 35° to approximately 29° in the
2 remaining 29 cycles (Figures 4-5).

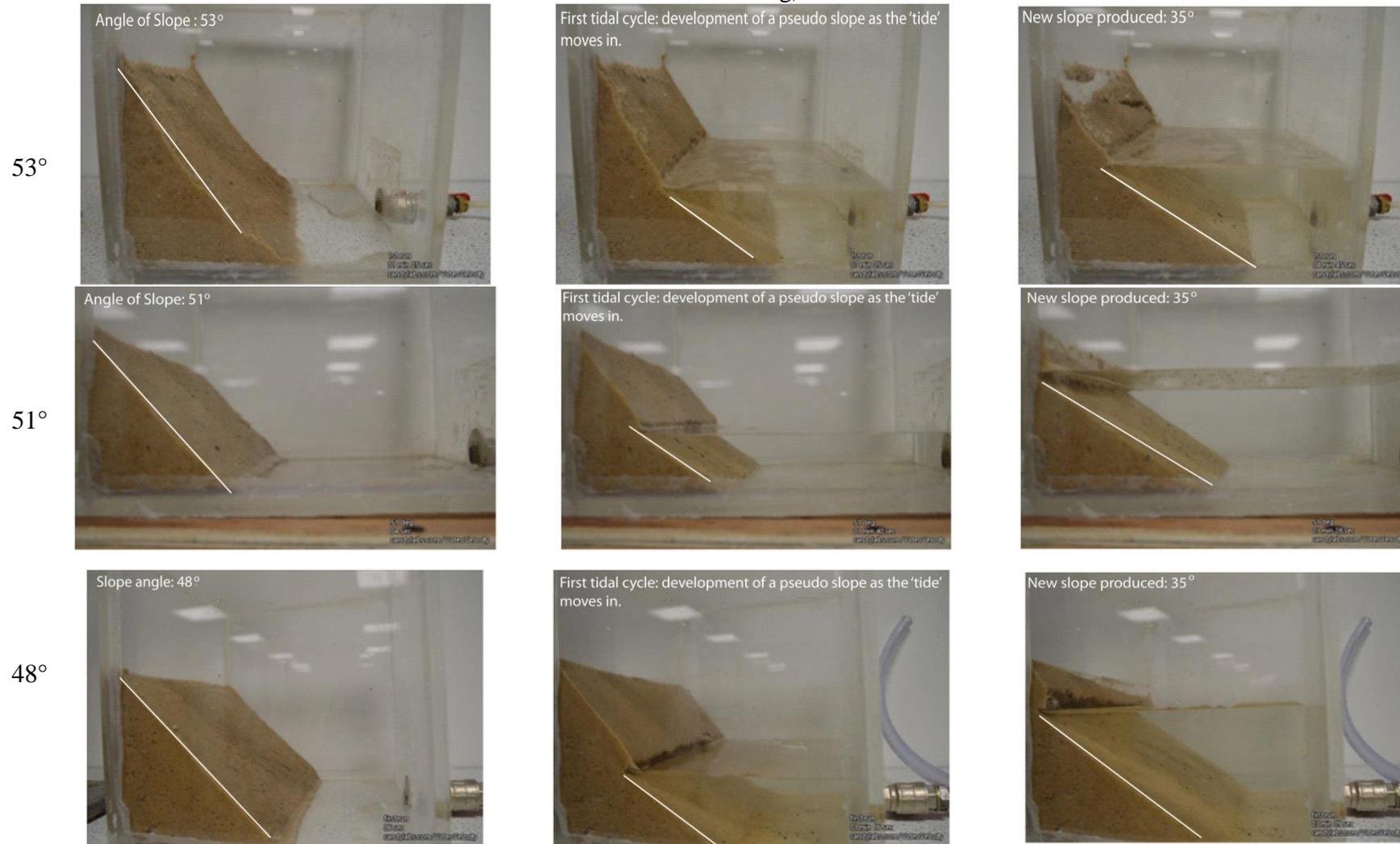
3 During the first tidal cycles, the force of the rising waters detached soil grains and circulated
4 them in the path of the current. Most of them settled and rolled down the slope further
5 destabilising other grains. Some grains deposited themselves at the foot of the slope, while others
6 stopped and settled slightly lower than their original position. The first tidal cycle resulted in the
7 development of a 'new' pseudo-slope beneath the saturated area as the tide moved upwards
8 (Figure 4). As the upsurge of water surpassed midpoint of slope height, the entire soil mass
9 above the waters collapsed. This instantly decreased slope height and increased slope length, a
10 typical 'rotational' type slope failure. The backwash was not as eventful; there was further
11 deposition of some fine particles in the tidal water as it receded along the slope surface. This
12 process was similar for all three soil masses/slopes tested (Figure 5).

13 The new slope formed after the initial collapse due to tidal effect was approximately 35° in all
14 three cases studied. This value is similar to the typical angle of repose measured for wet sandy
15 soils (i.e. 35.71°). There were no significant differences between the trends of slope change per
16 tidal cycle. The next 29 tidal cycles simulated showed gradual changes in the slope, which can
17 be interpreted as progressive erosion of surface sediments leading to decreasing slope height and
18 increasing slope length, albeit less drastic during these cycles compared to the first tidal cycle.
19 Similar observations for saturated sandy soil slopes of different heights in this study (48° - 53°)
20 justified the adoption of masses of 500g and 700g for forming slopes with corresponding slope
21 angles of 35° and 53° , respectively, in the experiments for MICP treated slopes.

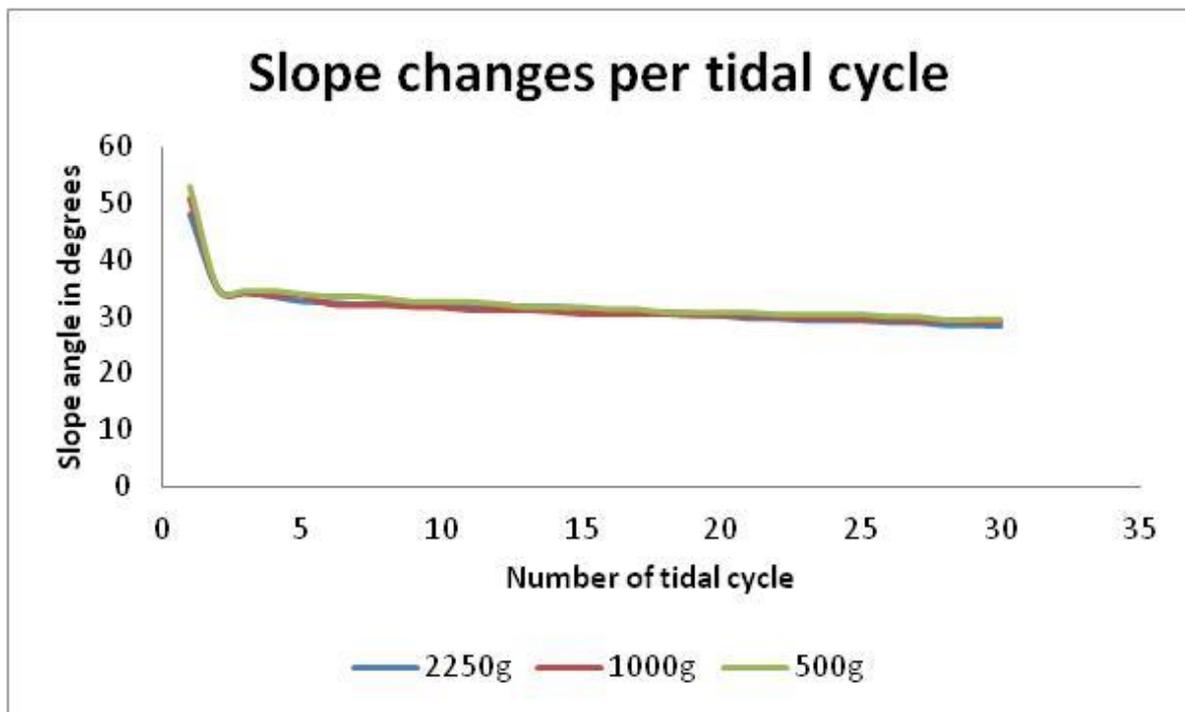
Commencement of tidal cycle uprush

Midway through uprush ('new' slope forming)

Final slope collapse



1 Figure 4: Slope collapse during first simulated tidal cycle uprush



1

2 **Figure 5: Changes in slope per tidal cycle simulated in all three soil masses (slope collapse and**
 3 **erosion phases)**

4 The mechanism of slope failure was found to be similar for all three steep slopes tested (48°, 51°
 5 and 53°) even though they were made up of different respective soil masses of 2250g, 1000 g
 6 and 500 g; this indicates that sandy soil slope failure and erosion mechanisms follow similar
 7 trends irrespective of the soil mass forming the slope. Further studies may be necessary to
 8 substantiate whether this can be extended to other scenarios.

9 The trend of erosion occurring after sandy soil slope failure (due to effects of tidal currents)
 10 obeys the linear function in the range investigated. The findings of this report indicate that
 11 foreshore sandy slope angles may decrease by approximately 0.2° for each tidal current cycle
 12 that occurs on it. An extrapolation of this relationship would give a fair idea of when the loss of
 13 foreshore may occur subject to the respective number of tidal cycles (although apparent linear
 14 functions would eventually become asymptotic). This is a very fundamental finding and may
 15 require further investigations that would put several variables in context to predict this trend
 16 more accurately.

1 **3.2 Examination of slope stability - *Experiments on treated sand slopes***: At the end of the
2 eighteen treatment cycles on each of the treated slopes (35° and 53°), thirty tidal current cycles
3 were simulated under the same water flow rates and conditions as used to establish slope failure
4 and erosion baselines (Section 2.2.1). This was done in order to make it easy to compare
5 stability between untreated and treated slopes subjected to tidal processes. Figures 6-7 show
6 slope failure and erosion occurrence for 53° and 35° slopes at selected tidal cycles in both
7 untreated and treated slopes. Graphical plot of the results for treated slopes of 35° and 53°
8 juxtaposed with untreated slopes (starting at the collapsed slope angle of 34.8°, where erosion
9 began, and slope angle of 53°, slope of instability) are as represented in Figures 8-9.

10 In both cases with the MICP, visual evidence showed negligible changes in the slope angle per
11 tidal cycle compared to what was obtained without treatment. Figures 6-7 emphasise the visual
12 differences as water rose mid-way the height of treated and untreated slopes in 1st, 2nd, 20th and
13 30th tidal cycles. The quantity of sediment deposited at the floor of the Perspex box (foot of
14 slope) visibly increased for untreated slopes per tidal cycle compared to the treated slopes.

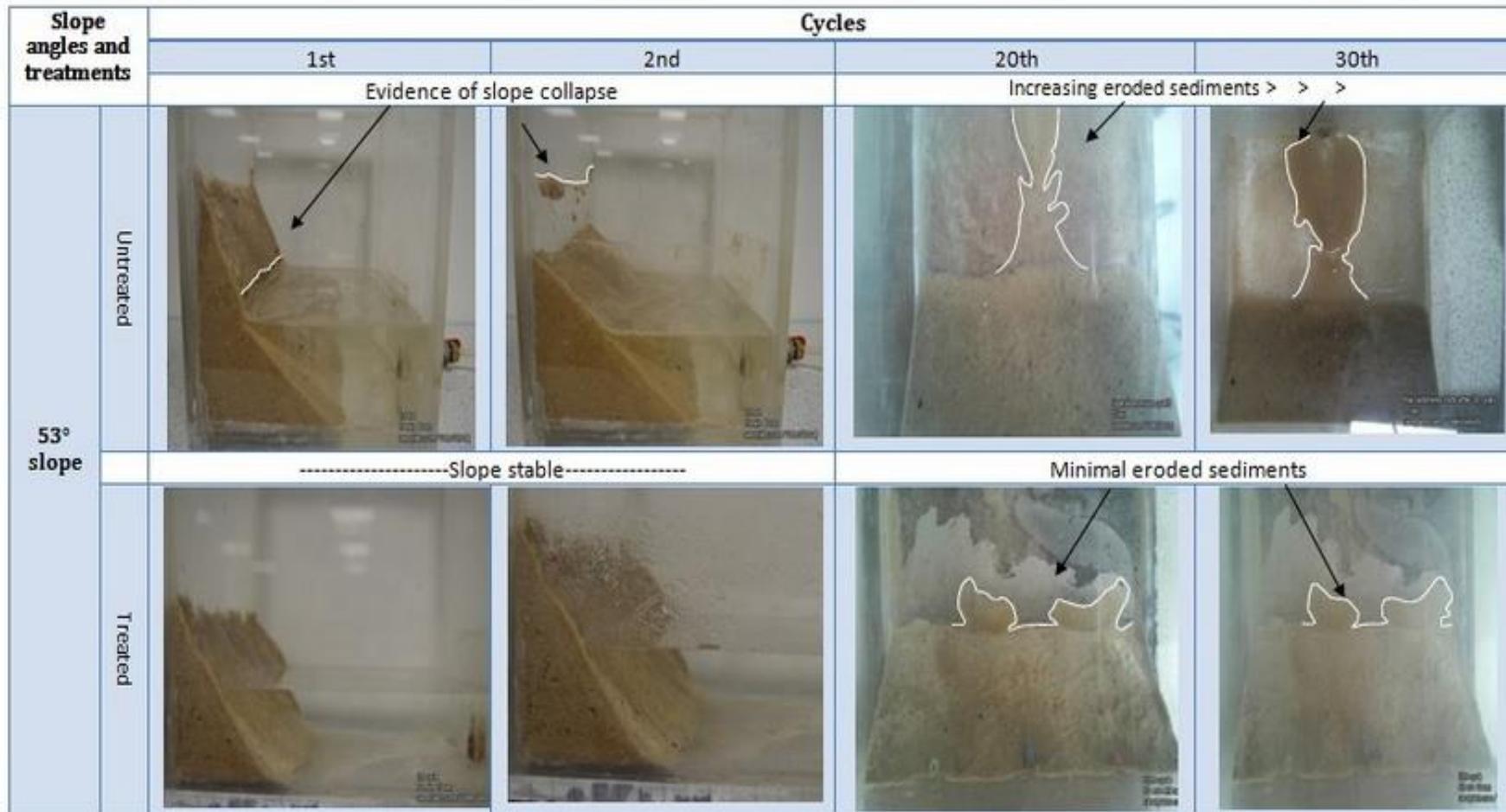
15 Clearly, Figures 6-9 imply that there was marked improvement in the treated sandy slopes as it
16 shows significant stability under the same tidal cycles that hitherto collapsed the untreated
17 slopes. MICP was capable of stabilizing the sandy soil slopes and also mitigated the erosion of
18 slope surface significantly. Broadly speaking, for an eroding/unstable sandy foreshore slope in
19 estuarine or coastal environments, application of MICP could potentially be effective in
20 cementing soil grains and thus mitigating slope failure or erosion to a reasonable extent.

21

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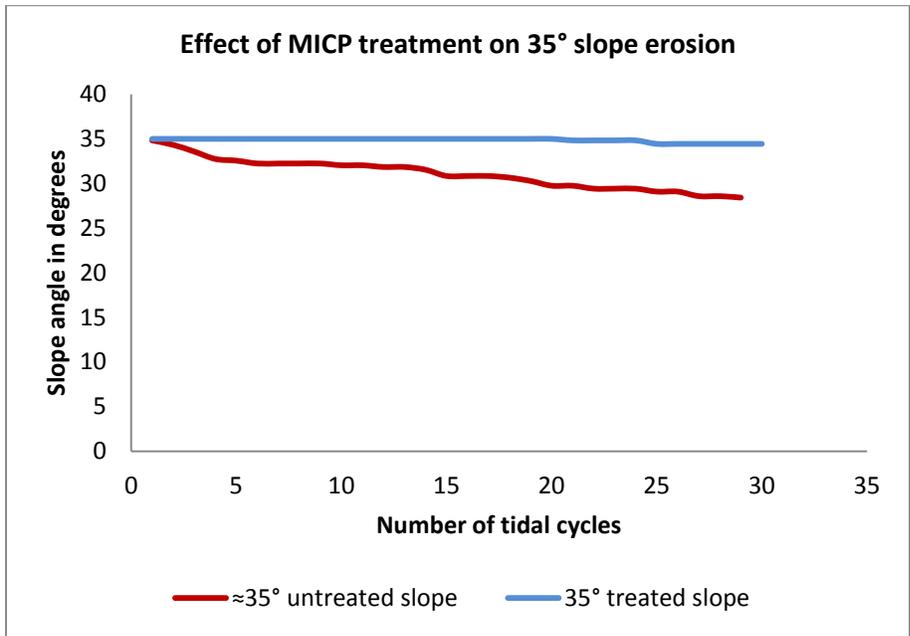


1

2 Figure 6. An array of images showing slope failure and erosion untreated 53° slope juxtaposed with MICP-treated slope at selected cycle of
 3 simulated tidal events.

4

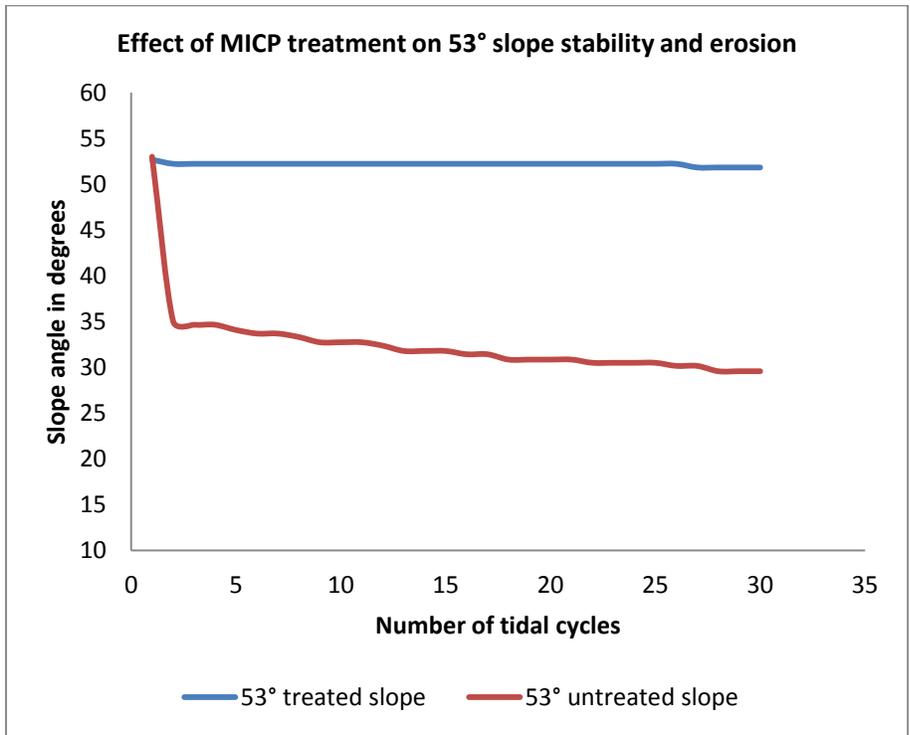
5



1

2 Figure 8: Graph comparing effect of MICP treatment on 35° slope erosion.

3



4

5 Figure 9: Graph comparing effect of MICP treatment on 53° slope erosion.

1 **3.3 Assessment of effectiveness of treatments**

2 Even though Section 3.2 and Figures 6-9 relatively show remarkable evidence of slope
3 improvement, we looked at the various possible evidences of calcite formation (visual evidence,
4 concentrations of effluent chemicals and mass balance after acid-washing of treated soils), and also
5 performed unconfined compressive strength tests on cemented soil cores so as to roughly estimate
6 its strength; these additional tests were meant to provide better understanding of the efficiency of the
7 MICP treatments on the treated soil slopes. In principle, these tests could also serve as indicators of
8 effective treatment in a field application. These are discussed in detail as follows:

9 *Visual evidence of calcite formation.*

10 Visual camera images showed a whitish fluid discharge from the foot of the slopes and staining the
11 floor of the Perspex box; this became more evident after the third treatment cycle (see Fig. S2) and
12 continued to increase in intensity in subsequent treatment cycles. White calcite patches became
13 visible also on the soil slope surface. The slopes were very rigid and firm after treatment to the
14 extent that it was difficult to detach the soil mass from the Perspex box.

15 *Concentration of ammonium and calcium from treatment effluents.*

16 Cation concentration in effluents, collected at foot of slope, provided an indication of MICP
17 performance (Table 4). The production of ammonium, a by-product of ureolysis, indicated that the
18 reactions for MICP were progressing. Ammonium fluctuations may be attributed to natural
19 variability, since bacteria were grown on different days and three treatment cycles were performed
20 per day. The *S. pasteurii* could have been at different metabolic activities during different cycles
21 despite efforts to normalise procedures.

22 The reverse trend was apparent for the concentration of calcium. Calcite production occurred as
23 reflected in the decreasing concentration of calcium in effluent; pore sizes may have reduced and

1 preferential nucleation of calcite on calcite (Tobler et al., 2011) may have also been the reason for
 2 this trend. Two pore volumes of 0.7 M CaCl₂ solution was injected into the soil per treatment cycle,
 3 leachate concentrations were between 0.14 M and 0.07 M calcium and suggest that most calcium
 4 was being retained in the soil.

5

6 **Table 4: Ammonium and calcium concentrations (mol/L) in effluent collected after selected**
 7 **number of treatment cycles.**

Sample concentration	Cycle 4	Cycle 7	Cycle 9	Cycle 11	Cycle 13
NH ₄ ⁺	0.044	0.046	0.12	0.038	0.11
Ca ²⁺	0.14	0.14	0.13	0.09	0.07

8

9 ***Mass balance after acid-washing of cemented soil***

10 A third evidence of calcite precipitation, and hence soil cementation, was the result of mass
 11 reduction from acid digestion. The cemented soils were removed from the Perspex box, oven dried
 12 and weighed before and after acid (10% HCl) dissolution of calcites (Table 5). Adequate precautions
 13 were taken to ensure only negligible loss of sand due to flushing. Calcite production amounted to
 14 approximately 118-155 kg per m³ of soil volume (or 4-5 mole CaCO₃ per litre of soil pore space).
 15 This was almost double the 60 kg calcite per m³ of soil (or 2 mol CaCO₃ per litre of soil pore space)
 16 termed as highly effective for MICP according to Al Quabany, et al. (2012). The percentage of pore
 17 spaces filled by cementation material (13.0% and 9.9% for 35° and 53° slopes) was also high
 18 compared to the 6%-10%, deemed as the standard when stabilizing soils for other geotechnical

1 applications (Stavridakis, 2005; Mehmanavaz et al., 2012; Oti and Kinuthia, 2012). This work
 2 achieved double the level of efficiency expected for a typical MICP treatment in terms of calcite
 3 precipitated in a particular media. Also, MICP treatment resulted in slight reduction in the pore
 4 volume; hence cemented soil retained significant portion of porosity, which would be significant for
 5 future activities such as agriculture/vegetation on the sandy soil foreshore slope.

6

7 **Table 5: Masses, volumes and amounts of calcite precipitated**

Treated slope angle	35°	53°
Mass of calcites precipitated in soil during treatment (g)	51.9	55.3
Volume of calcite precipitated (cm ³)	19.2	20.4
% Soil pores filled by calcite precipitated	13.0	9.87
Amount of calcite produced (kg m ⁻³ of soil)	155	118
Amount of calcite produced (mol L ⁻¹)	5.16	3.92

8 Assumptions (see Table S.2): dry density of sand, 1.49g cm⁻³; soil porosity, 0.44; specific gravity of
 9 calcite, 2.71; 1 kg calcite per m³ soil, (1/30) mol CaCO₃/litre of soil pore space (Al-Quabany, et al.,
 10 2012)

11

12 ***Strength of cemented soil***

13 To get a rough estimate of the strength of cemented soil, four cylindrical cores were taken from the
 14 treated slopes (Figure S3) and subjected to unconfined compressive strength (UCS) test. It should be
 15 noted that the height to diameter ratio (1.2:1; with heights between 18 mm and 25 mm and diameters
 16 between 15mm and 30mm) obtained from the cemented soil slopes is lower than 2:1 required for

1 triaxial compression test due the size of the slopes in the microcosm. Nonetheless, uniaxial
2 compressive strength recorded could be taken as an indication of the strength developed by the
3 microbial-induced precipitation of calcite.

4 All samples tested failed at average stress of 470 (± 3) kPa (Fig. S4). According to Collins and Sitar
5 (2009), sands with unconfined compressive strength of between 100-400 kPa are categorised as
6 moderately cemented, while below 100 kPa are weakly cemented sands. Going by this standard,
7 therefore, the ability of the cemented sands in this work to withstand this level of stress implies that
8 the MICP treatment achieved cementation above 'moderate' standards and with arguably
9 homogeneous strength distribution across the media.

10 These additional tests and their results further buttress the outcomes represented in Figures 6-9; it
11 has made explicit the fact that superlative amount of calcite was produced from the MICP process
12 and these was sufficient enough to bring about a highly cemented soil slope capable of resisting
13 collapse/failure and erosion under tidal current cycles.

14 **4.0 Conclusions**

15 Experimental microcosm demonstrated the mechanisms of slope failure and erosion obtainable on
16 foreshore sandy soil slopes. Sediment detachment occurred and subsequent tidal cycles continued to
17 erode the slope. After treatment with MICP, the treated slopes were visibly durable and filled up
18 9.9% of soil pores, which was almost double the benchmark for measuring MICP effectiveness (Al
19 Quabany et al., 2012; Oti and Kinuthia, 2012). Furthermore, the cemented soils exhibited
20 unconfined compressive shear strength classified as 'above moderate' (Collins and Sitar, 2009).
21 MICP treated soils were significantly more improved compared to untreated one subjected to the
22 same thirty tidal current cycles to check stability and erosion.

1 Erosion and slope stabilization issues are diverse and occur in varied locations/conditions. The
2 technique applied in this study for sandy soil stabilization and erosion mitigation have also shown
3 remarkable success in field trials aimed at ground reinforcement (van Paassen et al., 2009),
4 however, one of the greatest challenges in field trials experimented so far has been the non-
5 heterogeneous distribution or penetration of treatment across soil volumes; perhaps this may be due
6 to insufficient consideration of the limitations posed by boundary effects and other related factors
7 when up-scaling from laboratory based microcosms to field trials. These crucial aspects ought to be
8 adequately addressed if the objective is to modify strength and permeability uniformly across
9 relatively large volumes of soils. For protection from erosion and stabilization of an embankment's
10 slope, a relatively shallow penetration of treatment (10 - 20cm), would be sufficient; this should be
11 easy to achieve considering methodologies already experimented, with relative success, in the field.

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16

1 **References**

- 2 Agassi, M. and Ben, H.M. (1992). Stabilizing steep slopes with soil conditioners and plants. *Soil*
3 *Technol.* 5 (3): 249–256.
- 4 Al Quabany, A., Soga, K., and Santamarina, C. (2012) Factors affecting efficiency of microbially
5 induced calcite precipitation. *J. Geotech. Geoenviron. Eng.* 138 (8): 992–1001.
- 6 Amos, C.L., Brylinski, M., Lee, S., and O'Brien, D., (1996) Littoral mudflat stability monitoring, the
7 Number estuary, S. Yorkshire., England. *USPIJK, April 1995. Geological Survey of Canada Open*
8 *file report no. 3214.*
- 9 ASTM. (2004). Test specification for unconfined compressive strength of cohesive soil, D2166-00,
10 ASTM International, West Conshohocken, Pa.
- 11 ASTM. (2006). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil
12 Classification System), D2487-06e1. ASTM International, West Conshohocken, PA.
- 13 ASTM. (2007). Standard method for particle-size analysis of soils, D422-63e2. ASTM International,
14 West Conshohocken, PA.
- 15 Collins, B. D., and Sitar, N. (2009) Geotechnical properties of cemented sands in steep slopes. *J.*
16 *Geotech. Geoenviron. Eng.* 135(10):1359–1366.
- 17 Conley, D.C. and Griffin J.G. (2004) Direct measurements of bed stress under swash in the field. *J.*
18 *Geophys. Res.* 109:C03050 <http://dx.doi.org/10.1029/2003JC001899>.
- 19 Conley, D.C. and Inman D.L. (1994) Ventilated oscillatory boundary layers. *J. Fluid Mech.* 273:
20 262–284

- 1 Cowen, E.A., Sonu, I.M., Liu, P.L.F., and Raubenheimer, B. (2003) 'Particle image velocimetry
2 measurements within a laboratory-generated swash zone'. *J. Eng. Mech.* 129: 1119–1129.
- 3 Cox, D.T., Hobensack, W., and Sukumaran, A. (1998) 'Bottom stress in the inner surf and swash
4 zone'. *Proceedings of the 27th International Conference on Coastal Engineering, ASCE*: 108–119.
- 5 Dejong, J.T., Soga, K., Kavazanj, I.E., Burns S., Van Paassen, L.A., Al Qabany, A., Aydilek, A.,
6 Bang, S.S., Burbank, M., Caslake, L.F., Chen, C.Y., Cheng, X., Chu, J., Ciurli, S., Esnault-Filet, A.,
7 Fauriel, S., Hamdan, N., Hata, T., Inagaki, Y., Jefferis, S., Kuo, M., Laloui, L., Larrahondo, J.,
8 Manning, D.A.C., Martinez, B., Montoya, B.M., Nelson, D.C., Palomino, A., Renforth, P.,
9 Santamarina J.C., Seagren, E.A., Tanyu, B., Tsesarsky, M., and Weaver, T. (2013) Biogeochemical
10 processes and geotechnical applications: progress, opportunities and challenges. *Geotechnique*
11 63(4): 287–301.
- 12 DeJong, J.T., Fritzges, M.B., Nusslein, K. (2006) Microbial induced cementation to control sand
13 response to undrained shear. *J. Geotech. Geoenv. Engrg, ASCE.* 132(11): 1381–1392.
- 14 DeJong, J.T., Martinez, B.C., Mortensen, B.M., Nelson, D.C., Waller, J.T., Weil, M.H., Ginn, T.R.,
15 Weathers, T., Barkouki, T., Fujita, Y., Redden, G., Hunt, C., Major, D., and Tanyu, B. (2009)
16 Upscaling of bio-mediated soil improvement. *Proceedings of the 17th International Conference on*
17 *Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt.*
- 18 El Mountassir, G., Lunn, R., Moir, H., and MacLachlan, E.C. (2014) Hydrodynamic coupling in
19 microbially mediated fracture mineralization: formation of self-organized groundwater flow
20 channels. *Water Resources Res.* 50: 1-16.
- 21 Elfrink, B. and Baldock, T. (2002) Hydrodynamics and sediment transport in the swash zone: a
22 review and perspectives. *Coast. Eng.* 45: 149–167.

- 1 Esnault-Filet, A., Gadret, J.P., Loygue, M. and Borel, S. (2012) Biocalcis and its application for the
2 consolidation of sands. In: Johnsen, L. F., Bruce, D. A. and M. J. Byle (eds.), *Grouting and deep*
3 *mixing*. Geotechnical Special Publication 288. Reston, VA, USA: ASCE. Vol. 2, pp. 1767–1780.
- 4 Fang, H.W. and Wang, G.Q. (2000) Three-dimensional mathematical model for suspended sediment
5 transport. *J. Hydraul. Eng., ASCE*. 126(8): 578–592.
- 6 Fang, N.F., Shi, Z.H., Yue, B.J., and Wang, L. (2013) The characteristics of extreme erosion events
7 in a small mountainous watershed. *PLoS One* 8(10): e76610.
- 8 Ferris, F.G., Stehmeier, L.G., Kantzas, A., and Mourits, F.M. (1996) Bacteriogenic mineral
9 plugging. *J. Can. Petr. Technol.* 35 (8): 56–61.
- 10 Fujii, T., and Raffaelli, D. (2008) Sea-level rise, expected environmental changes, and responses of
11 intertidal benthic macrofauna in the Humber estuary, UK. *Mar. Ecol. Prog. Ser.* 371: 23–35.
- 12 Haller, M.C., Honegger, D., and Catalan, P.A. (2014) Rip current observations via marine radar. *J.*
13 *Waterway, Port, Coastal, Ocean Eng.* 140: 115-124.
- 14 Harkes, M.P., Booster, J.L., van Paassen, L.A., van Loosdrecht, M.C.M. (2008) Microbial induced
15 carbonate precipitation as ground improvement method –bacterial fixation and empirical correlation
16 CaCO_3 vs. strength. *1st International Conference on Bio-Geo-Civil Engineering, Netherlands; June*
17 *23- 25*. pp. 37–41.
- 18 Harkes, M.P., van Paassen, L.A., Booster, J.L., Whiffin, V.S., and van Loosdrecht, M.C.M. (2010)
19 Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground
20 reinforcement. *Ecol. Eng.* 36: 112–117.

- 1 Ivanov, V., and Chu, J. (2008) Applications of microorganisms to geotechnical engineering for
2 bioclogging and biocementation of soil in situ. *Rev. Environ. Sci. Biotechnol.* 7: 139–153.
- 3 Liu, D., and Li, Y. (2003) Mechanism of plant roots improving resistance of soil to concentrated
4 flow erosion. *J. Soil Water Conserv.* 17(3): 34–37.
- 5 Liu, J., Shi, B., Huang, H., and Jiang, J. (2009) Improvement of water-stability of clay aggregates
6 admixed with aqueous polymer soil stabilizers. *Catena.* 77: 175–179.
- 7 Liu, J., Shi, B., Jiang, H., Huang, H., Wang, G., and Kamai, T. (2011) Research on the stabilization
8 treatment of clay slope topsoil by organic polymer soil stabilizer. *Eng. Geol.* 117: 114-120.
- 9 Longo, S., Petti, M., and Losada, I.J. (2002) Turbulence in the swash and surf zones: a review.
10 *Coast. Eng.* 45: 129-147.
- 11 MacMahan, J., Thornton, E.B., and Reniers, A.J.H.M. (2006) Rip current review. *J. Coast. Eng.* 53
12 (2-3): 191 - 208.
- 13 Masselink, G., Evans, D., Hughes, M.G., and Russell, P. (2005) Suspended sediment transport in the
14 swash zone of a dissipative beach. *Mar. Geol.* 216 (3): 169-189.
- 15 Mehmannaavaz, T., Bhutta, M.A.R., Sumadi, S.R., and Sajjadi, M. (2012) Stabilization of desert sand
16 in Iran using cement and microsilice. *AES-ATEMA Tenth International Conference on Advances and*
17 *Trends in Engineering Materials and their Applications.* Montreal, Canada: June 18 – 22.
- 18 Mitchell, J.K., and Santamarina, J.C. (2005) Biological considerations in geotechnical engineering.
19 *J. Geotech. Geoenviron. Eng. ASCE.* 131(10): 1222–1233.
- 20 Mitchell, A.C., Dideriksen, K., Spangler, L.H., Cunningham, A.B., and Gerlach, R. (2010)
21 Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping.
22 *Environ. Sci. Technol.* 44: 5270 - 5276. Doi 10.1021/es903270w.

- 1 Miura, K., Maeda, K., and Shosuke, T. (1997) Method of measurement for the angle of repose of
2 sand. *Soils Foundat.* 37(2): 89-96.
- 3 Oti, J.E., and Kinuthia, J. M. (2012) Stabilised unfired clay bricks for environmental and sustainable
4 use. *Appl. Clay Sci.* 58: 52-59.
- 5 Petti, M., and Longo, S. (2001) Turbulence experiments in the swash zone. *Coast. Eng.* 43: 1–24.
- 6 Scot, T., Russell, P., Masselink, G., and Wooler, A. (2009) Rip current variability and hazard along
7 a macro-tidal coast. *J. Coast. Res.* Special issue 56: 895-899.
- 8 Sharples, C., (2006) Indicative Mapping of Tasmanian Coastal Vulnerability to Climate Change
9 and Sea-Level Rise: Explanatory Report (Second Edition); *Consultant Report to Department of*
10 *Primary Industries & Water, Tasmania.*
- 11 Short, A.D. and Brander, R. (1999) Regional variation in rip density. *J. Coast. Res.* 15: 813-822.
- 12 Short, A.D. (1985) Rip current type, spacing and persistence, Narrabeen beach, Australia. *Mar.*
13 *Geol.* 65: 47–71.
- 14 Singh, A. K. (2010) 'Bioengineering techniques of slope stabilization and landslide
15 mitigation. *Disaster Prevention and Management.* 19, pp. 384-397.
- 16 Stavridakis, E.I. (2005) Evaluation of engineering and cement–stabilization parameters of clayey–
17 sand mixtures under soaked conditions. *Geotech. Geol. Eng.* 23: 635–655.
- 18 Tobler, D. J., Cuthbert, M. O., Greswell, R. B., Riley, M. S., Renshaw, J. C., Handley- Sidhu, S.
19 and Phoenix, V. R. (2011) 'Comparison of Rates of Ureolysis between *Sporosarcina pasteurii* and
20 an Indigenous Groundwater Community under Conditions Required to Precipitate Large Volumes
21 of Calcite'. *Geochim. Cosmochim. Acta*, 75:3290–3301.

- 1 Uzunoglu, E., Bicer, A.Z.Y., Dolapci, I. and Dogan, A. (2014) Biofilm-forming ability and
2 adherence to poly-(methyl-methacrylate) acrylic resin materials of oral *Candida albicans* strains
3 isolated from HIV positive subjects. *J. Adv. Prosthodont.* 6(1): 30–34.
- 4 Van Paassen, L.A., Harkes, M.P., Van Zwieten, G.A., Van der Zon, W.H., Van der Star, W.R.L. and
5 Van Loosdrecht, M.C.M. (2009) Scale up of BioGrout: a biological ground reinforcement method.
6 *Proceedings of 17th International Conference of Soil Mechanical and Geotechnical Engineering,*
7 *Alexandria, Egypt* pp. 2328–2333.
- 8 Van Paassen, L.A., Ghose, R., van der Linden, T.J.M., van der Star, W.R.L., and van Loosdrecht,
9 M.C.M. (2010) Quantifying biomediated ground improvement by ureolysis: large-scale biogrout
10 experiment. *ASCE J. Geotech. Geoenviron. Eng.* 136: 1721–1728.
- 11 Van Paassen, L.A., Whiffin, V.S. and Harkes, M.P. (2007) Immobilization of bacteria to a
12 geological material. *Netherlands Patent assignee Stichting GeoDelft.* EP1798284-A1;
13 WO2007069884-A1.
- 14 Whiffin V.S., Van Paassen, L.A., and Harkes, M.P. (2007) Microbial carbonate precipitation as a
15 soil improvement technique. *Geomicrobiol. J.* 24(5): 417–423.
- 16 Winn, P.J.S., Young, R.M., and Edwards, A.M.C. (2003) Planning for the rising tides: the Humber
17 Estuary Shoreline Management Plan. *Sci. Tot. Environ.* 314–316: 13–30.
- 18

1 Supplemental Information

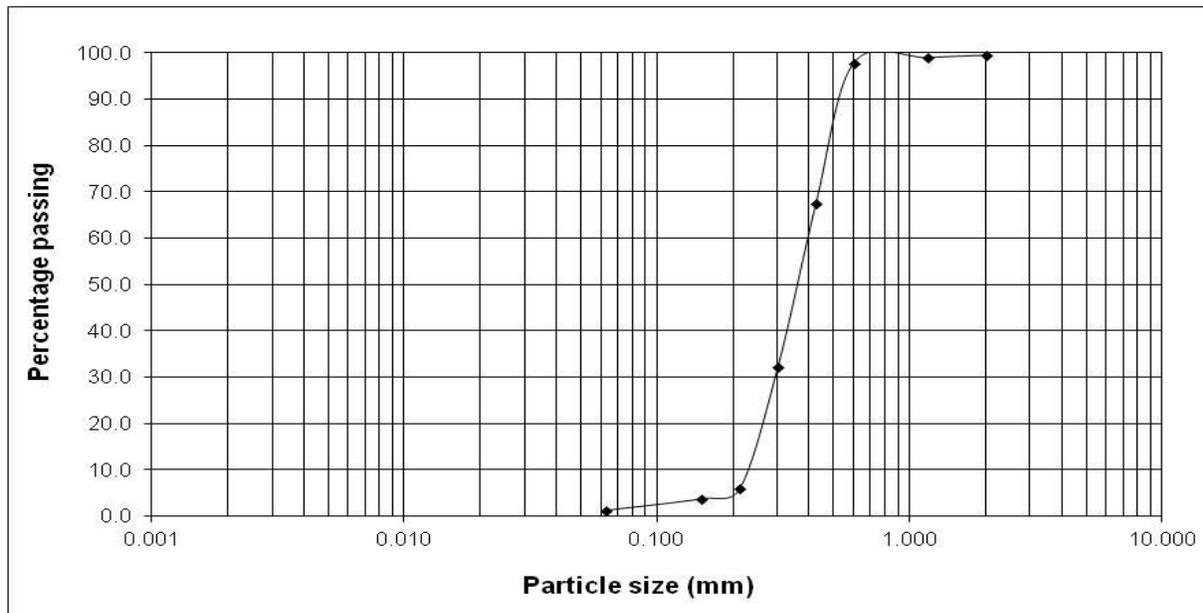
2 **Application of microbially induced calcite precipitation in erosion**
3 **mitigation and stabilization of sandy soil foreshore slopes**

4
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7 ^b Department of Civil Engineering, Indian Institute of Technology-Bombay, Mumbai, India

8
9 **Supplemental figures:**



11
12 **Figure S1: Grain size distribution curve representing the sand used in the experiments. Sand was**
13 **collected from Troon beach, Ayrshire, U.K.**

1

35°

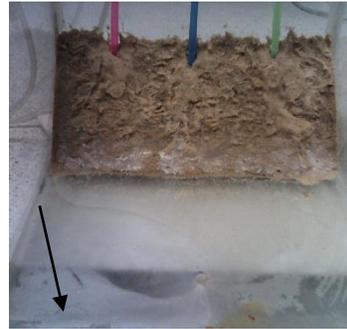
Before treatment



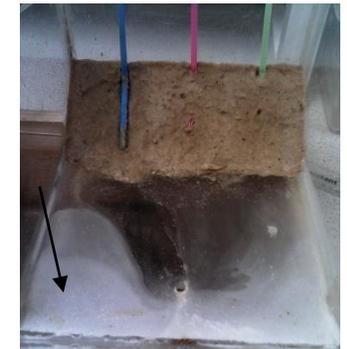
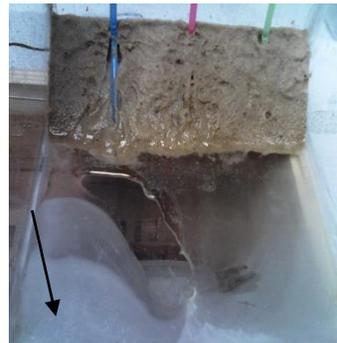
At 3rd treatment cycle



At 18th treatment cycle



53°



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1 **Figure S2: Visual evidence of calcite precipitation as treatment progressed.** Arrows show whitish
2 fluid on floor of Perspex box; see also the white patches on soil surface.

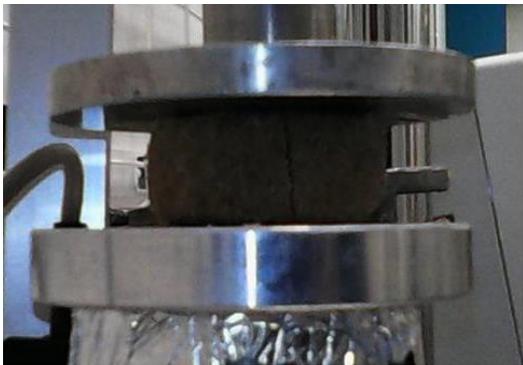
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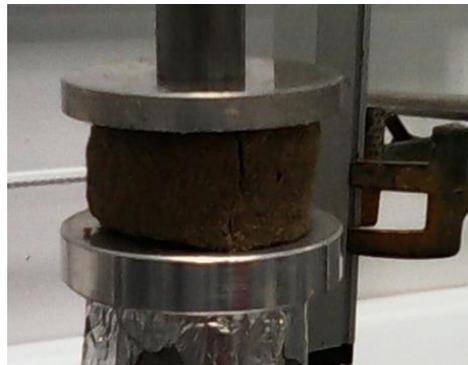
(a)



(b)



(c)

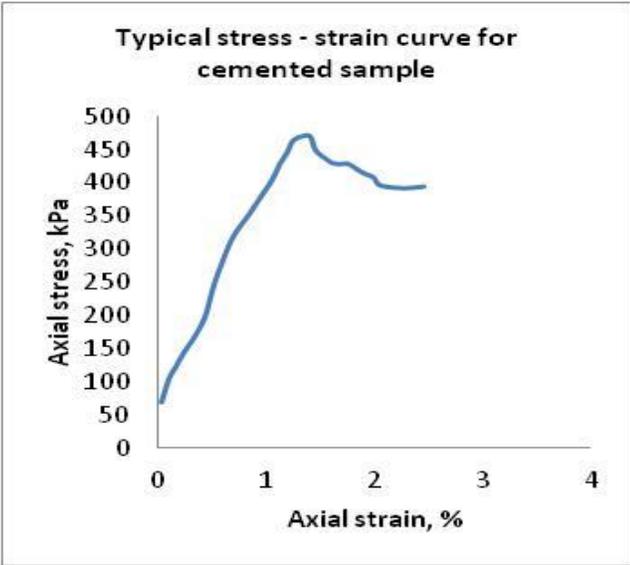


(d)

4

5 **Figure 3: (a and b) core sampling points and (c and d) failed cores under UCS testing machine.**

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Figure S4: A typical stress-strain graph of the samples subjected to UCS test.

1 **Supplemental tables**

2 **Table S.1: Constituents of Blood Heart Infusion (BHI) agar and BHI broth**

Media	Components	Mass proportion (gL ⁻¹ of distilled water)
BHI agar	Brain Heart, Infusion from (solids)	8.0
	Dextrose	2.0
	Peptic Digest of Animal Tissue	5.0
	Disodium Phosphate	2.5
	Pancreatic Digest of Casein	16.0
	Agar	13.5
	Sodium Chloride	5.0
BHI broth	beef heart (infusion from 250g)	5.0
	calf brains (infusion from 200g)	12.5
	disodium hydrogen phosphate	2.5
	D(+)-glucose	2.0
	peptone	10.0
	sodium chloride	5.0

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1 **Table S.2: Masses, volumes and amounts of calcite precipitated.**

	Treated slope angle	35°	53°
a	Mass of oven-dried soil before treatment (g)	500	700
b	Volume of soil treated (cm ³) [(a/1.49 g cm ⁻³ *)]	335.57	469.80
c	Pore volume of dry soil treated (cm ³) [(b x 0.44**)]	147.65	206.71
d	Mass of oven-dried cemented soil at end of treatment (g)	541.00	754.75
e	Mass of oven-dried soil after acid washing (g)	489.07	699.45
f	Mass of calcites precipitated in soil during treatment (g) [d - e]	51.93	55.30
g	Volume of calcite precipitated (cm ³) [f/2.71***]	19.16	20.41
h	% Soil pores filled by calcite precipitated [(g/c) x 100]	12.98	9.87
i	Amount of calcite produced kg m ⁻³ of soil [f/b x 1000]	154.75	117.70
j	Amount of calcite produced Mol L ⁻¹ [i x (1/30)****]	5.16	3.92

2 *Dry density of sand = 1.49g cm⁻³; **Soil porosity = 0.44; *** Specific gravity of calcite = 2.71;

3 ****1 kg calcite per m³ soil = (1/30) mol CaCO₃ per litre of soil pore space (Al-Quabany et al,

4 2012)

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