MICROBIALLY INDUCED CALCITE PRECIPITATION (MICP) TO MITIGATE CONTACT EROSION IN EARTH EMBANKMENT DAMS AND LEVEES

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ABSTRACT

Internal erosion of water retaining structures (such as earth embankment dams, levees and dykes) is a major geotechnical problem. Contact erosion is a specific type of internal erosion that occurs at the interface between fine and coarse soils, for instance along the downstream edge of the core-filter interface, and can lead to earth dam failure due to internal erosion. Although in new dams this may be avoided by fulfilling the filter criteria or with the construction of barriers, retrofitting older structures often entails significant design and construction costs due to the uncertainties surrounding their materials and behaviour. In this context, microbially induced calcite precipitation (MICP), a bacteria-induced bio-mineralisation process capable of binding soil particles in situ, provides a cost-effective alternative for contact erosion control. However, it is necessary to establish a solid understanding of how biogenic cementation occurs at the interface between fine and coarse sands and its influence on the erosion and hydro-mechanical characteristics.

This paper studies the erosion of MICP treated fine sand and coarse sand combinations with flow parallel to the surface of the fine-grained fraction. For this purpose, an Erosion Function Apparatus (EFA) has been built and tested. Water flows through a rectangular flume and erodes the soil specimen, which protrudes 1 mm above the bottom of the flume. Results identify the patterns of biomineralisation and provide insight into which parameters have a first-order effect on the erosional behaviour and shear strength profile of fine-grained cemented sands. By comparing these results with typical critical shear stress values encountered in real dams, it is recognised that different optimal improvement thresholds to previous biocementation works published in the literature are necessary in the dam sector.

INTRODUCTION

Internal erosion is a major cause of dam incidents, causing almost 50% of all embankment dam failures (ICOLD 2016). Although embankment dam engineering has increasingly evolved over the last century, it remains very difficult to assess the long-term performance of existing dams that do not meet modern design criteria as they may have significant deficiencies in regards to material capability. This is the case of the downstream granular filters of older structures, which, if at all existent, may not necessarily reflect current filter design practice and could be susceptible to contact erosion (CE). This phenomenon develops at the interface between two soils with different grain sizes and permeabilities due to the shear stress of interface-parallel flow and can

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thus occur at the downstream edge of the core-filter interface and along the core-foundation boundary. Indeed, although the hydraulic gradient in both layers is approximately the same, the difference in permeability will cause the velocity in the coarse layer to be much higher than that in the fine one. This velocity gradient will induce a shear stress on the upper particles of the fine layer, triggering detachment. If these particles find an unfiltered exit, erosion will initiate. CE is, therefore, the result of the coupling of two mechanisms: a mechanical instability and a hydraulic instability.

ICOLD (2016) distinguishes two different approaches to control internal erosion: filters and barriers. While they are both sensible methods to reduce the risk of internal erosion, in the long term, filter effectiveness within the dam may be reduced and new pathways may open up around these barriers. While for new dams these problems may be avoided with proper design, retrofitting older structures often entails significant design and construction costs, as well as service interruption. Within this context, microbially induced calcite precipitation (MICP), a bio-mediated soil improvement technique, is emerging as a viable alternative. The current study focuses on MICP using the bacterium *Sporosarcina pasteurii* to hydrolyse urea. This process raises the pH of the system and results in the availability of carbonate ions, which, in the presence of calcium, trigger the precipitation of calcium carbonate (calcite). The precipitated calcite binds soil particles together and improves the erodibility of sand.

The focus of this study was to examine the effect of biological treatment on the contact between two sands with different grain sizes and permeabilities and to determine the effects of MICP on the critical shear stress and the mechanism of particle movement with horizontal flow in a laboratory flume situation. Details of specimen preparation, characterisation methods, and shear stress resistance facilitate the examination of the degree to which MICP may provide additional opportunities over other existing technologies.

MATERIALS AND METHODS

Specimen Preparation

Control of MICP on an interface between fine and coarse sands was examined in the context of a series of 100 ml one-dimensional flow sand column experiments, as shown in Figure 1. This experimental setup was previously described by Rebata-Landa (2007) and Al Qabany (2011). Syringes were dry packed with Fraction A overlying Fraction D or E silica sand (resulting in a relative density ranging between 90 and 95%) and connected to plastic tubing to allow nutrient circulation. A filter was placed at the bottom to avoid fine particles from being washed-out by the solution and electrical tape was used to avoid leakage. Specimens were then flushed with deionised (DI) water to establish their pore volume (PV), or pore space, as well as to remove air pockets and ensure a controlled flow field. The total injection volume of DI water was 2 PV to ensure complete saturation.

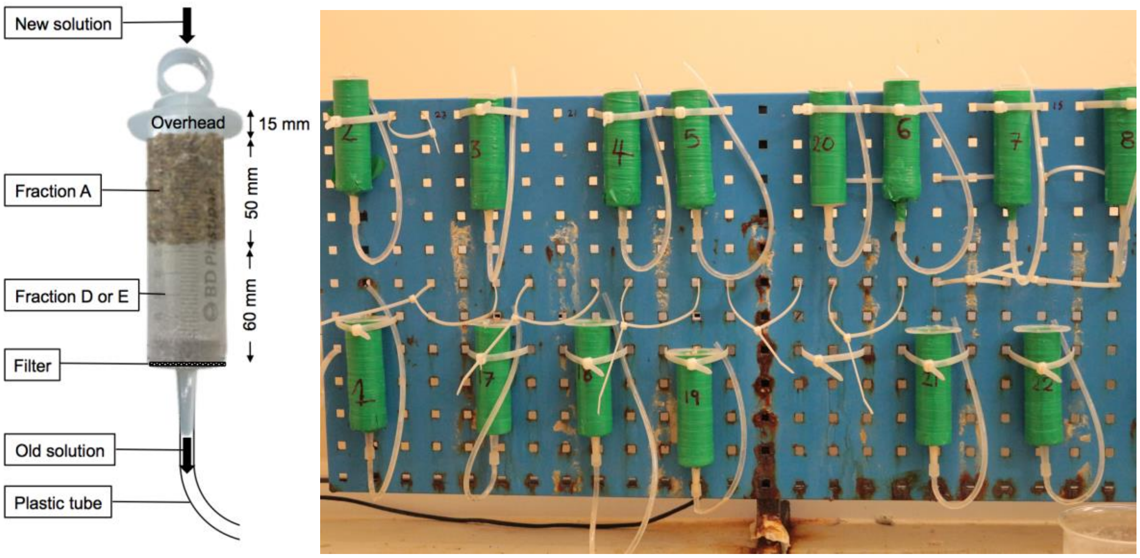

Figure 1. One-dimensional flow sand column experiments: (left) specimen preparation; (right) specimens during retention time.

Bacterial and Cementation Solutions

Sporosarcina pasteurii ATCC 11859, formerly *Bacillus pasteurii*, is the bacterial strain that was chosen for this study, because it is ubiquitous in soil, non-pathogenic, and does not require processing before use. Bacteria were harvested and inoculated under sterile conditions in a NH_4-YE medium that contained: 20 g/l of yeast extract, 10 g/l of ammonium sulphate, and 0.13 M of Tris buffer (Table 1). These components were used to regulate the pH of the solution and to offer a source of carbon and energy (Dawoud 2015). All ingredients were autoclaved separately in a sterilizer for 20 minutes and left to cool down prior to mixing and introducing the concentrated bacterial colonies. This solution was then placed in a shaking incubator for 24 hours.

Many different formulations for the cementation solution are available in the literature, which primarily differ in the calcium chloride ($CaCl_2$) concentration, the molar ratio between urea and $CaCl_2$, and the retention time[3] (DeJong et al. 2006; Rebata-Landa 2007; Whiffin et al. 2007; Al Qabany 2011). Al Qabany 2011 examined the effect of different urea-$CaCl_2$ concentrations and retention times (6, 12 and 24 hours) on the precipitation pattern. He created three different nutrient solutions containing an equimolar amount of urea and $CaCl_2$ (0.25, 0.5 and 1 M), 3 g of nutrient broth, 2.12 g of sodium bicarbonate ($NaHCO_3$) and 10 g of ammonium chloride (NH_4Cl) per litre of distilled water. Results showed that the use of lower chemical concentrations in injections results in a better distribution of calcite precipitation and recommended using normalised loading rates[4] of less than 0.042 M/l/h. Rebata-Landa 2007 used the same nutrient treatment formulation, but varied the ratio of [Urea]:[$CaCl_2$]. Results suggested that calcium carbonate ($CaCO_3$) content increases with the nutrient concentration, however, reported efficiencies were

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[3] Time between MICP treatment injections.

[4] Normalised loading rate (M/l/h) = Solution concentration (M/l) / Time of treatment (h) (Al Qabany 2011).

very low. A possible explanation for this is that, for high $CaCl_2$ concentrations, urea was always the limiting factor, hindering the ATP generation and, consequently, the hydrolysis of urea. The effects of urea to calcium ratio on the ureolysis and calcite precipitation were also studied by Martinez et al. (2013) and concluded that recipe formulations should be designed with a ratio greater than 1. Therefore, a cementation solution with a molar ratio of [Urea]:[$CaCl_2$] = 3:2 was used.

Additionally, Al Qabany (2011) reported that the main chemicals required for MICP are urea (carbonate source) and $CaCl_2$ (calcium source), and that the use of some chemicals such as NH_4Cl and $NaHCO_3$, which act as pH stabilisers, is not crucial for the process. On this basis, two different samples treated with cementing solutions with and without NH_4Cl were created and the pH of the outflow solution was measured every 24 hours. It was found that, for the nutrient concentrations used in this study, 2.12 g/l of $NaHCO_3$ were enough to stabilise the pH. From this point onwards, the term urea-$CaCl_2$ medium will be used to refer to the chemical solution that contains all the constituents listed in Table 1.

Table 1. Summary of microbial induced cementation treatment formulations.

Solution	Constituent		Concentration
Initial biological treatment	Yeast extract		20 g/l
	Ammonium sulphate		10 g/l
	Tris buffer		0.13 M/l
	S. pasteurii		OD_{600} = 0.8-1.2
Urea-$CaCl_2$ medium	Urea*	$CO(NH_2)_2$	0.375 M/l
	Calcium chloride*	$CaCl_2$	0.25 M/l
	Sodium bicarbonate	$NaHCO_3$	2.12 g/l
	Nutrient broth		3 g/l

*A nutrient solution with a molar ratio of [Urea]:[CaCl2] = 3:2 was used.

MICP Treatment Program

The MICP treatment was divided into two stages. In the first (biological phase), 1 PV of the bacteria solution was injected from the top by gravity and left to set within the specimen for 24 hours to allow for microbes to attach to the particles (DeJong et al. 2006). In the seconds (cementation) phase, 1 PV of the nutrient solution (Table 1) was injected in the same way and the old solution was allowed to drain out of the specimen. To ensure that the sample remained saturated between injections, the plastic tubing was put up and a solution overhead was left at the top, as shown in Figure 1. This process of injection-retention of the nutrient solution was repeated every 24 hours until the desired level of calcite cementation was attained.

The termination of each test involved draining all the remaining liquid solution and flushing with DI water to remove excess material. After removing the specimen from the syringe, it was oven dried to stop the metabolism.

CHARACTERISATION METHODS/EXPERIMENTAL METHODS TO ASSESS CEMENTATION EFFECTS

Monitoring of MICP induced changes in the mechanical and hydraulic properties of sands included spatial and temporal measurements of the calcite content, the hydraulic conductivity, and the shear strength.

Calcium Carbonate Content

Calcium carbonate content was measured after treatment completion by mixing 30 ml of hydrochloric acid with 30 g of dried sample in an enclosed cylinder, called calcimeter. This reaction leads to the dissolution of calcite and the release of carbon dioxide, resulting in a pressure increase proportional to the calcite content of the sample.

Hydraulic Conductivity

Hydraulic conductivity was also analysed after treatment using a falling head test for the column setup in Figure 1.

Specimen Shearing

A new Erosion Function Apparatus (EFA), shown in Figure 2, was built to measure the erodibility of MICP treated sands. A similar experimental setup was proposed by Briaud et al. (1999) for estimating the erosion of soil at bridge piers and was classified as a potential method for assessing the susceptibility of soils to CE by Fell & Fry (2005).

Specimens were placed through a circular opening in the bottom of a rectangular cross-section flume (70 mm by 25 mm in cross section and 1 m long). Tap water was poured into a water tank and was driven into the flume by a pump. Water flowed into the flume through a pipe and a flow meter was used to measure the flow rate. A flow straightener was placed close to the inlet to avoid a water jet effect. The specimen was placed in an acrylic mould and leveled with the bottom of the rectangular flume. An extruding screw at the bottom end of the specimen was used to push the soil until it protruded approximately 1 mm into the flume (Figure 3). A laser was installed on top of the flume to measure the height of sample eroded throughout the test, and a camera, taking a frame of the surface of the sample every 4 minutes, was installed to identify erosion patterns.

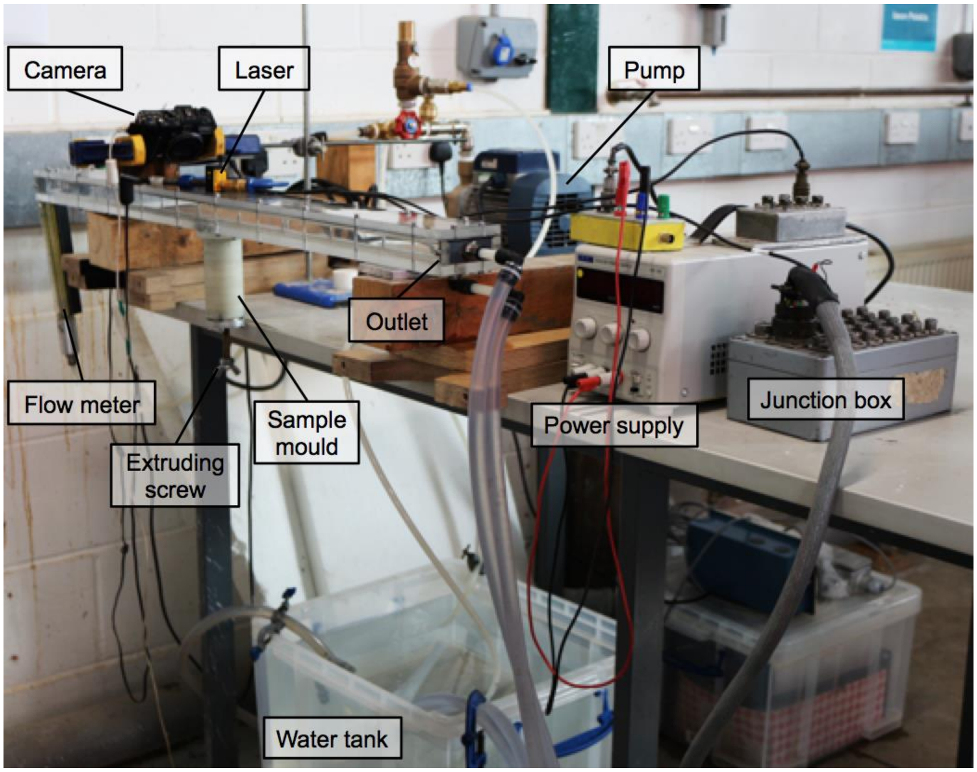

Figure 2. EFA experimental setup.

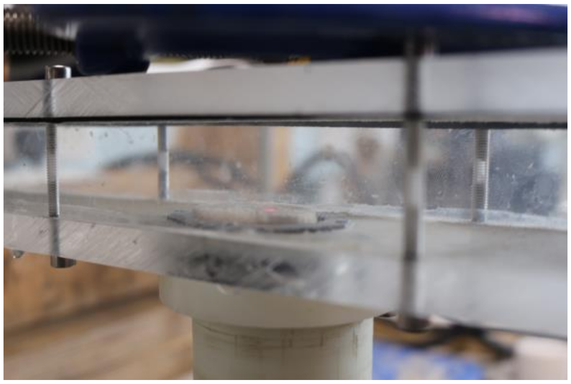

Figure 3. Side view of the 1 mm protrusion into the flow.

RESULTS AND DISCUSSION

Calcium Carbonate Distribution

Controlling MICP on an interface between fine and coarse sands requires spatial knowledge of the cementation. For this purpose, the calcite content of two specimens (after 6 and 14 injections of urea-$CaCl_2$ medium) was measured at seven different points along their height. Results are shown in Figure 4. In both cases, calcite concentration was highest near the interface between coarse and fine particles. However, the calcite profile evolved from relatively asymmetric for 6 injections, where a lower concentration was measured in the Fraction A sand, to a more symmetric one for 14 injections. Given that the permeability of the Fraction A sand is significantly higher than that of the Fraction D sand, the former acts as a filter causing the urea-$CaCl_2$ medium to flow straight into the Fraction D, cementing it first. After precipitation, the pore space of the Fraction D is reduced, partially interrupting the chemical transport in this fraction and causing it to remain within the Fraction A sand. Such a restraint of the urea-$CaCl_2$ medium favours the cementation of the Fraction A sand at later stages of the treatment.

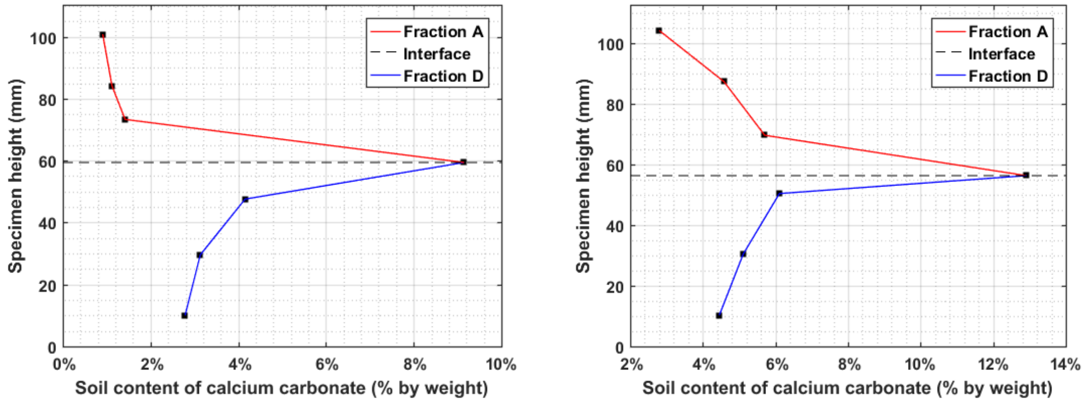

Figure 4. Effect of the interface on the calcite cementation: (left) specimen after 6 injections; (right) specimen after 14 injections of the urea-$CaCl_2$ medium.

The preferential cementation near the interface, approximately 2-times greater than in the bulk material, could be attributed to the spatially varying attached bacteria distributions along the specimen. Ford & Harvey (2007) recognised the role of chemotaxis for the migration of bacteria towards “increasing concentrations of chemicals that they perceive as beneficial to their survival.” During the first injections, the urea-$CaCl_2$ medium is accumulated at the interface due to the hydraulic constraint imposed by the Fraction D sand (the velocity of urea-$CaCl_3$ medium is significantly reduced when flowing from a high to a low permeability material). Since bacteria are able to sense through receptor molecules, they respond to this chemical gradient and preferentially attach to the soil grains located at the interface (Ford & Harvey 2007).

It is worth noting, however, that this preferential cementation along the interface offers an additional advantage for CE control in that it allows to selectively attain high calcite concentrations along the target zone with a low number of injections. Most MICP investigators to date have focused on achieving spatial uniformity of cementation (Martinez et al. 2013; Al Qabany & Soga 2013; Dawoud 2015), thus, these results reveal that the important parameters for the application of MICP for CE control are yet to be evaluated.

Changes to Hydraulic Conductivity

In order to avoid leakage, the hydraulic conductivity was measured before removing the specimen from the syringe for the measurement of the calcite content. Therefore, it is clear that in a one-dimensional specimen this was controlled by the zone in the finer material with the highest calcite content, i.e. the interface. Figure 5 shows that the hydraulic conductivity decreased during the MICP treatment as a result of void space reduction. Although the measurements varied even for specimens subject to the same treatment, it was found that a rapid reduction of permeability occurred at the beginning of the treatment (less than 2 injections), with permeability then remaining constant until 6-8 injections, after which permeability decreased sharply. This trend provided insight into the calcite distribution within the pore space and agreed with previous studies reported in the literature (Jiang 2016).

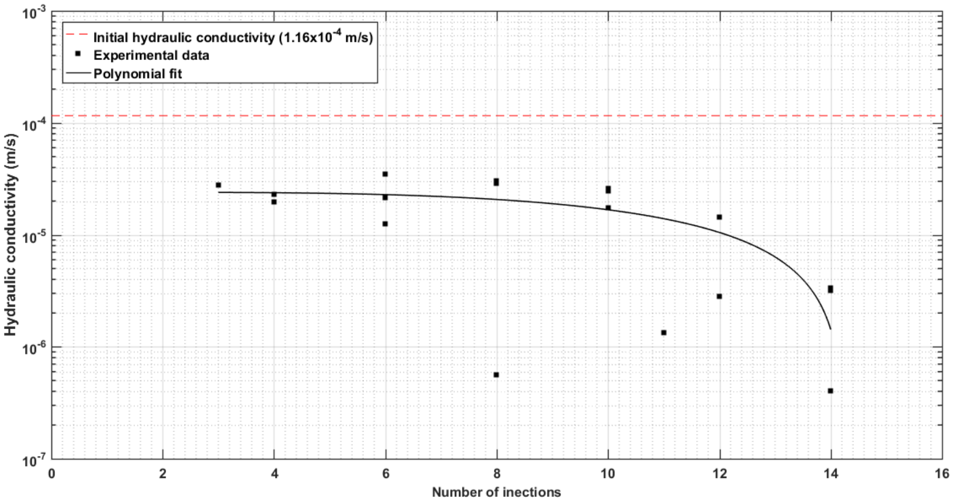

Figure 5. Effect of the number of injections of urea-$CaCl_2$ medium on the hydraulic conductivity.

Microbes have a general preference for positioning themselves in the pore throats (DeJong et al. 2006). Therefore, for a low number of injections, calcite links soil particles through bridging and leaves the large pores relatively open so that the change in hydraulic conductivity is rather small. As the number of injections increases, calcite interparticle connections grow in thickness and become interconnected, reducing the pore throat space and, consequently, the hydraulic conductivity. Therefore, if a low number of injections are needed for CE control, MICP offers the advantage of cementing the grains at pore constrictions while hardly influencing the water flow.

Shear Stress at Soil-Water Interface

Measurements of the surface movement of the eroding sample were made with a laser reflecting on the soil surface in the flume. The progress of erosion could hence be monitored as the flow velocity was increased. The cumulative height eroded (che) versus the velocity was the result of the EFA tests conducted. In order to investigate the shear strength profile a new parameter called erodibility, $S = d(che)/dv$, was defined, which represents the rate of change of the che with the velocity. Indeed, the area under this curve is equal to the probability density function of particles eroded. For example, the cumulative percentage of particles eroded for a velocity y is equal to the area below the erodibility function comprised between 0 and y. This is schematically shown in Figure 6. Evidently, the erodibility curve can also be obtained in terms of the shear stress applied by the water at the bottom of the flume.

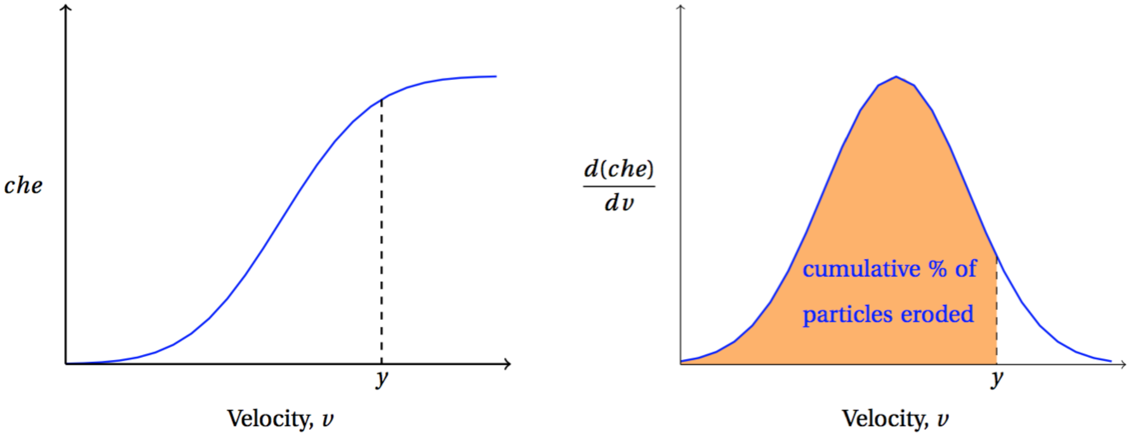

Figure 6. Conceptual diagrams of the EFA data analysis: (left) cumulative height eroded versus velocity curve; (right) erodibility curve.

Four different Fraction D samples with different degrees of cementation were tested and the results are shown in Figures 7-9, in order of lowest to highest calcite concentrations. Generally speaking, MICP treatment triggered an increase in the critical velocity v_c required to initiate erosion and reduced the che beyond that point. For instance, the che beyond $v_c = 0.167$ m/s reached 0.22 for a sample with 1.06% of $CaCO_3$ (Figure 7), while for a sample with 3.31% of $CaCO_3$ it only reached 0.036 mm (Figure 10). Therefore, by tripling the soil calcite content, the che decreased by a factor of 10.

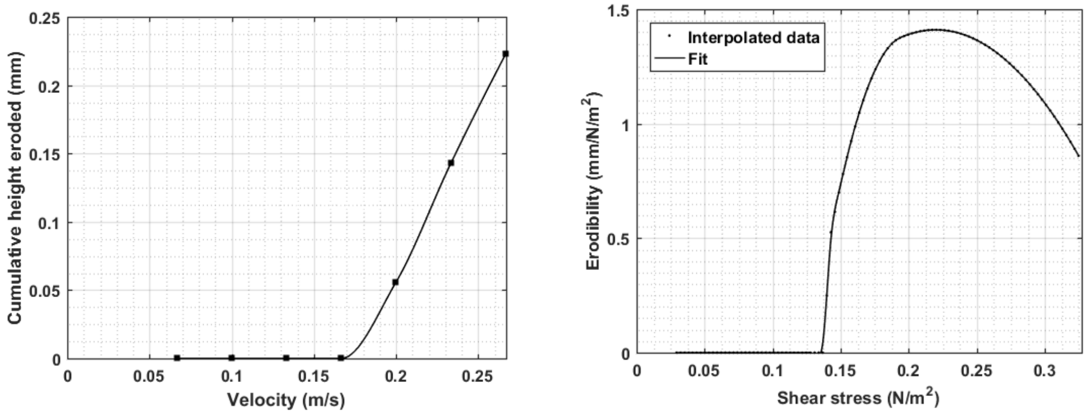

Figure 7. Specimen with 1.06% of $CaCO_3$.

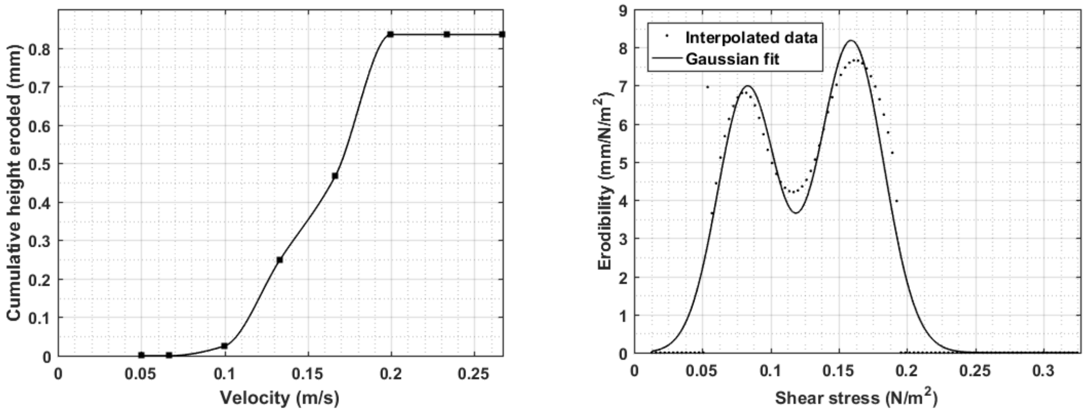

Figure 8. Specimen with 1.76% of $CaCO_3$.

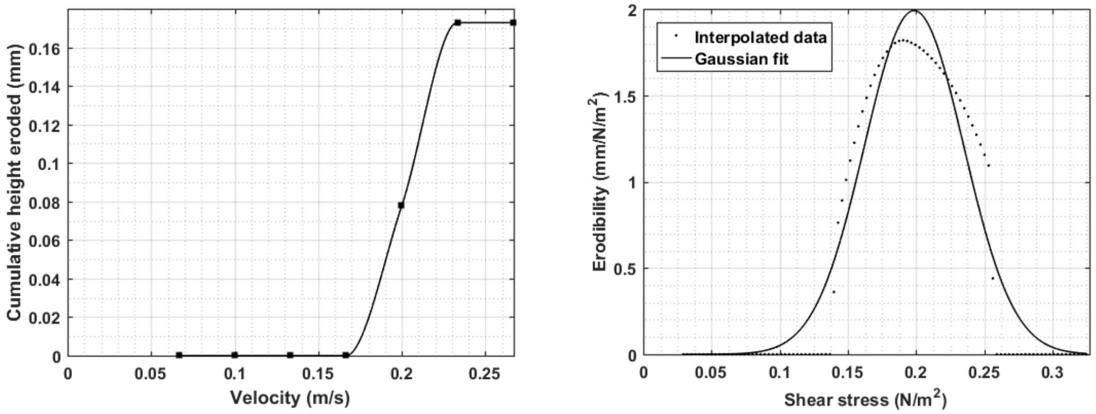

Figure 9. Specimen with 2.34% of $CaCO_3$.

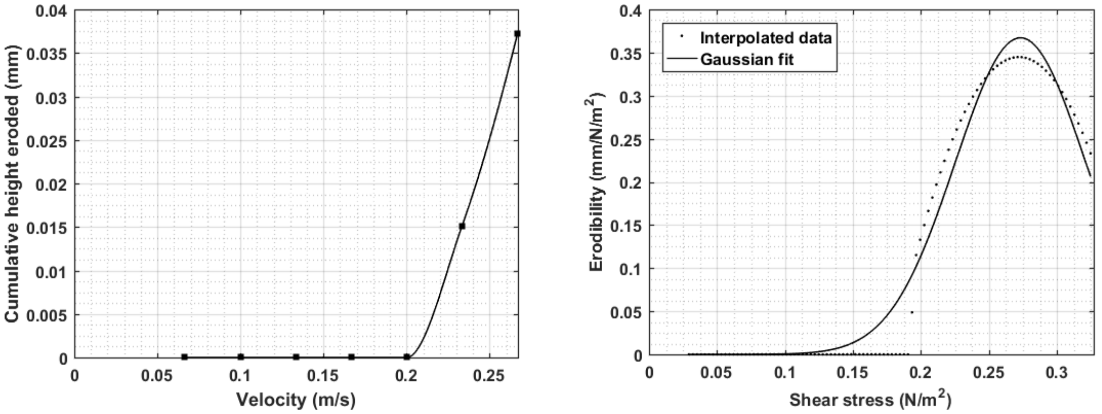

Figure 10. Specimen with 3.31% of $CaCO_3$.

While the most common shape of the erodibility function for untreated fine-grained soils agrees with the concept introduced in Figure 6 (Briaud et al. 1999), the scenario for MICP treated sands was quite different. In order to explain what initially seemed like unusual behaviour, one needs to understand how the binding of particles degrades with loading. Under shear hydraulic loading, specimens may be eroded as a result of a fracture within the precipitated calcite or due to the detachment of uncemented particles (DeJong et al. 2010). At lower shear stresses there is no breakage of calcite-calcite bonds and only uncemented or very weakly cemented particles erode. This suggests that MICP treatment caused specimens to have two discontinuous shear strength profiles, one associated with the uncemented or weakly cemented particles (A_w) and the other with the calcite bonds (A_s), as shown in Figure 11. Predictably, a weakly cemented specimen will not only have a big A_w, but also a second bell shape curve which is smaller and shifted to the left (as there is a smaller proportion of calcite-calcite bonds). This results in two curves with boundaries that become progressively less clear as the $CaCO_3$ content of a specimen decreases – which is the case of Figure 8 and justifies its high erodibility values.

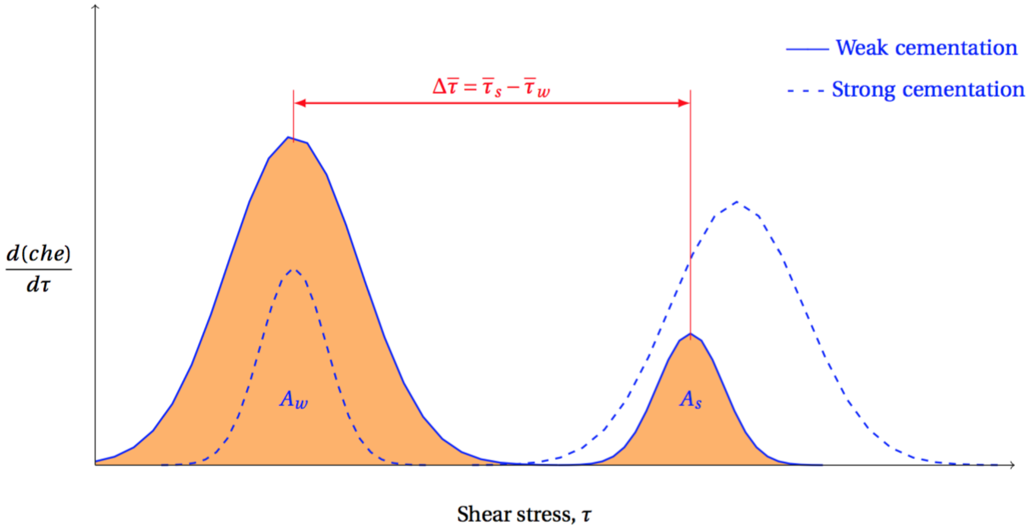

Figure 11. Conceptual diagram of the strength profile for MICP treated sands.

IMPLICATIONS FOR FIELD IMPLEMENTATION

Implementation of laboratory-tested techniques in the field not only depends on understanding how the modification of soil characteristics may provide additional opportunities over other existing technologies (such as grouting), but also on identifying the level of improvement required for CE control in earth dams.

The critical hydraulic gradient at which local heave from the base material into the pores of the filter material occurs is (Perzlmaier 2005):

$$i_c = \{0.7 \text{ to } 0.8\} \frac{(1-n)(\gamma_s-\gamma_w)}{\gamma_w} \tag{1}$$

γ_w being the specific weight of water and $\gamma_s - \gamma_w$ that one of soil under uplift. For a typical porosity $0.25 \leq n \leq 0.48$ and a specific weight of the particles of 26 kN/m^2, the critical gradient ranges between $0.58 \leq i_c \leq 0.96$ (Perzlmaier 2005). Khilar et al. (1985) found a relationship between critical pressure gradient J and critical shear stress τ_c required to initiate erosion:

$$J = \frac{\tau_c}{2.828}\left(\frac{n_0}{\kappa_0}\right)^{\frac{1}{2}} \tag{2}$$

where n_0 is the porosity before erosion and κ_0 is the permeability of the soil. Real embankment dams are generally built with materials with a hydraulic conductivity ranging between 10^{-4} m/s (well graded sands and gravels) and 10^{-8} m/s (clays and silts), giving typical values ranging between $0.0008 \leq \tau_c \leq 0.172$ N/m^2. In comparison to previous biocementation works performed at a sample scale where the objective was to produce sandstone like masses to carry loads, the shear strength increase necessary on interfaces potentially vulnerable to CE in the field is very low. It is predicted that calcite contents varying between 2.5% and 3% will be enough for this purpose (cf. Figure 9 and Figure 10). Additional consideration of the interface effect discussed previously could further reduce these values.

CONCLUSIONS

First, control of MICP on an interface between fine and coarse sands was examined in the context of a series of 100 ml one-dimensional flow sand column experiments. This study confirmed that the distribution of microbes plays a fundamental role for achieving a uniform calcite precipitation. However, hydraulic constraints associated with the local interruption of the transport of urea-$CaCl_2$ medium across the interface causes bacteria to exhibit chemotactic responses, yielding calcite concentrations approximately 2-times higher in the interface than in the rest of the specimen. It is clear, then, that this zone controls the measurements of the hydraulic conductivity. Results enabled to identify two phases of behaviour. During the first phase, no significant changes in the hydraulic conductivity were observed. However, during the second phase, a significant reduction was observed; this was attributed to the thickening and subsequent interconnection of the calcite bonds.

A new Erosion Function Apparatus (EFA) was built and tested to measure the erodibility of MICP treated sands. Results revealed that MICP causes sands to have a discontinuous strength profile in the shape of a double bell curve, where the relative distance between the two peaks decreases as the calcite concentration decreases. Thus, it seems that a threshold exists between transient erosion, linked to initial particle by particle surface washing, and steady erosion, linked to a block by block erosion process. Although the definition of this threshold is still unclear, it was found that its determination may require the mobilisation of very high shear stresses (in the range of the hundreds of kN/m^2).

From a practical standpoint, the experiments conducted in this research enabled the identification of a suitable improvement threshold for CE control, which was found to be much lower than the one needed for other biocementation applications studied in the literature. For the typical shear stresses encountered in real dams, results suggested that a calcite content ranging between 2.5-3% would be sufficient. This, together with the retention of the hydraulic conductivity, and the preferential attachment of bacteria along the interface zone, make MICP very attractive for CE control and could have significant implications to dam safety risk reduction.

To date, no field trials using MICP in water-retaining structures have been reported in the literature. However, two successful bioclogging attempts to reduce the hydraulic conductivity of 'leaking' dykes were reported in the Netherlands and Austria (Blauw et al. 2009). Although bioclogging differs from MICP in that natural microbes are stimulated rather than injected into the soil, similar injection techniques to the ones used to inject the nutrient-rich solution could be adopted. These include the use of a screen of injection wells in the crest of the structure or releasing both the bacteria and nutrient solutions in the upstream reservoir. While cost estimates for MICP treatment vary widely (from US\$25 – 75/m^3 to about US\$500/m^3), studies have shown that the major cost is in delivery (Dejong et al. 2013). Hence, if this can be done economically, strong potential exists. However, to better understand its durability and performance over the structure's service life and the potential implementation constraints that could lead to additional costs, MICP treatment still requires further development. This should involve larger scale laboratory testing and extending to field trials.

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