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Application of microbially induced calcite precipitation in erosion mitigation and stabilisation of sandy soil foreshore slopes: A preliminary investigation

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ABSTRACT

Eroding foreshores endanger the floodplains of many estuaries, as such, effective and environmentally friendly interventions are sought to stabilise slopes and mitigate erosion. As a step in forestalling these losses, we developed laboratory microcosms to simulate tidal cycles and examined the mechanisms of erosion and failure on sandy foreshore slopes. As an experimental aim, we applied microbially induced calcite precipitation (MICP) to selected slopes and compared the effectiveness of this microbial geo-technological strategy to mitigate erosion and stabilise slopes. To assess shoreline stability, thirty cycles of slowly simulated tidal currents were applied to a sandy slope. Significant sediment detachment occurred as tides moved up the slope surface. For steeper slopes, one tidal event was sufficient to cause collapse of the slopes to the soil's angle of repose (~35°). Subsequent tidal cycles gradually eroded surface sediments further reducing slope angle (on an average 0.2° per tidal event). These mechanisms were similar for all slopes irrespective of initial slope inclination.

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

1. Introduction

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

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

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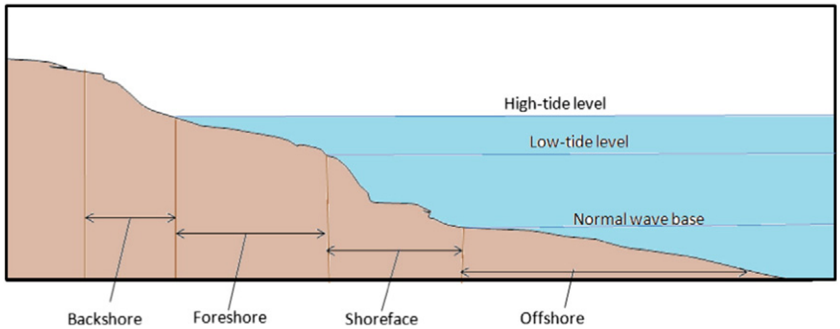

Fig. 1. Typical coastal/estuary anatomy showing foreshore, tide levels and other shores.

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

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

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

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

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

The application of the MICP techniques for stabilising foreshore slopes still remains a budding line of research. Meanwhile, laboratory investigations to understand soil erosion processes have been reported in the literature, but little has been done regarding coastal foreshore slopes. The closest investigations, linking laboratory studies of water-induced soil erosion and/or stabilisation to MICP treatment, were done by Van Paassen et al. (2010) and Esnault-Filet et al. (2012). Even though their work involved treatment of saturated soils, it did not consider soils at slopes, their erosion mechanism, nor the effects of intermittent tidal currents on soil slopes. Here, the experimental laboratory-scale microcosms aim to demonstrate slope failure and erosion mechanisms on soil slopes as tidal processes occur and to test the potential effectiveness of MICP in stabilising such slopes and mitigating slope surface erosion. This microcosm approach is an advantageous preliminary step, which provides an experimental approach at laboratory scale, where environmental factors can be controlled, and scaled down models of actual soil slopes could be investigated. Subsequently, other complex variables may be introduced as a build-up towards large-scale field implementation of findings.

1.1. Background

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

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_3 + H_2CO_3^{2-} \quad (1)$$

Ammonia in the presence of water forms ammonium and hydroxyl ions, which increases ambient pH around the bacterial environment to about 9 (Eq. (2)) (DeJong et al., 2006; Van Paassen et al., 2009), and the resultant alkaline environment shifts the carbonate systems to ultimately producing more carbonate ions (Eqs. (3)–(4)):

$$2NH_3 + H_2O \leftrightarrow 2NH_4 + 2OH^- \quad (2)$$

$$H_2CO_3 + 2OH^- \leftrightarrow HCO_3^- + H_2O + OH^- \quad (3)$$

$$HCO_3{}^- + H_2O + OH^- \leftrightarrow CO_3^{2-} + 2H_2O \quad (4)$$

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

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3(s)} \quad (5)$$

Calcite crystals serve as the 'cementing bridges,' which bind soil grains together, and they have been found to be highly effective in binding soil particles up to 50 years and improving their geotechnical properties, such as shear strength (DeJong et al., 2009). Cementation, whether obtained from bio-cementation or bio-clogging, depend on several factors, such as the following: 1) bacterial aggregation (El Mountassir et al., 2014); 2) the composition and concentration of