Soil engineering in vivo: harnessing natural biogeochemical systems for sustainable, multi-functional engineering solutions

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Carbon sequestration, infrastructure rehabilitation, brownfields clean-up, hazardous waste disposal, water resources protection and global warming—these twenty-first century challenges can neither be solved by the high-energy consumptive practices that hallmark industry today, nor by minor tweaking or optimization of these processes. A more radical, holistic approach is required to develop the sustainable solutions society needs. Most of the above challenges occur within, are supported on, are enabled by or grown from soil. Soil, contrary to conventional civil engineering thought, is a living system host to multiple simultaneous processes. It is proposed herein that ‘soil engineering in vivo’, wherein the natural capacity of soil as a living ecosystem is used to provide multiple solutions simultaneously, may provide new, innovative, sustainable solutions to some of these great challenges of the twenty-first century. This requires a multi-disciplinary perspective that embraces the science of biology, chemistry and physics and applies this knowledge to provide multi-functional civil and environmental engineering designs for the soil environment. For example, can native soil bacterial species moderate the carbonate cycle in soils to simultaneously solidify liquefiable soil, immobilize reactive heavy metals and sequester carbon—effectively providing civil engineering functionality while clarifying the ground water and removing carbon from the atmosphere? Exploration of these ideas has begun in earnest in recent years. This paper explores the potential, challenges and opportunities of this new field, and highlights one biogeochemical function of soil that has shown promise and is developing rapidly as a new technology. The example is used to propose a generalized approach in which the potential of this new field can be fully realized.

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considers contaminants within the soil; plant science considers suitability for plant growth and to maximize the productivity of crops. Soil is a finite resource and it commands our stewardship [3,4].

The gravity of the situation is sinking in. Sustainability concepts and soil reuse planning are being implemented for select practices in first world countries. New construction is evaluated against carbon footprint, energy efficiency and total life-cycle analysis criteria (e.g. [5,6]). Unfortunately, the burgeoning world population demands still outpace the ‘savings’ gained by these reformations, such that the pace of consumption (and associated environmental impact) continues to increase. A more radical, holistic approach is required.

Herein, the potential for ‘soil engineering in vivo’, for soil to be considered as a living, active system that has the capacity to provide multiple sustainable solutions simultaneously, is explored. This requires a multidisciplinary perspective that embraces the science of biology, chemistry and physics, and applies this knowledge to multi-functional civil and environmental engineering applications. For example, can native soil bacterial species moderate the carbonate cycle in soils to simultaneously solidify liquefiable soil, immobilize reactive heavy metals and sequester carbon—effectively providing civil engineering functionality while clarifying the ground water and removing carbon from the atmosphere? Exploration of these ideas has begun in earnest in recent years, and this paper explores the potential, challenges and opportunities of this new field, highlights one biogeochemical function of soil that has shown promise and is developing rapidly, and proposes a generalized approach in which the potential of this new field can be fully realized.

2. ENVISIONING THE POSSIBILITIES...

Visions of the potential are emerging more rapidly than technical capabilities. Green Wall Sahara, an anti-desertification initiative that consists of stabilizing a 6000 km reach of sand dunes across northern Africa has been proposed by Magnus Larsson ([7]; figure 1a). One-quarter of the world’s land mass, which is home to more than one billion people across 100 countries is threatened by desertification [8]. Specifically, Mauritania’s capitol, Nouakchott, is on the verge of succumbing to this threat (figure 1b), and in Nigeria the desert is moving southward 600 m yr⁻¹. Larsson’s idea is impossible using conventional soil-solidification measures based on concrete and chemicals, but stimulating and harnessing a natural process inherent to living soil—such as the bio-mediated calcification process discussed herein—might realize this dream.

Biologically aided carbon sequestration enabled by pedogenic carbonate precipitation, which occurs near plant root exudates in highly alkaline soil, may be an untapped naturally occurring reservoir primed to address this global issue. Plants exude 10–30% of the carbon captured from the atmosphere, by photosynthesis, through their roots and associated mycorrhizal fungal associations ([9,10] and included references). Any compound in the root tissue may be released into the soil in the form of an exudate (see [11]); thus root exudates are a complex material composed of polysaccharides, proteins, phospholipids, cells that detach from the external layers of the root and many other compounds. Respired CO₂ and organic acid anions that naturally decompose and can react with calcium-rich silicates within soils are of particular interest. David Manning (Newcastle University) and others [12] have documented that this process occurs naturally in soils at brownfields sites [13]. Cement and iron/steel production produces about 10 per cent of the world’s carbon emissions. As proposed in figure 2, it may be possible to re-sequester a portion of this carbon into the subsurface through the admixing of recycled concrete and furnace slag into soils used for non-food crops and urban re-vegetation [14].

Stimulating and controlling naturally occurring biological processes provide an innovative solution for remediation of metal-contaminated ground water and soil in situ (e.g. [15,16]). Robert Smith (University of Idaho) and colleagues are attempting to co-precipitate radioactive heavy metals—such as strontium 90 (⁹⁰Sr), a uranium fission byproduct and carcinogen—with calcite, effectively immobilizing ⁹⁰Sr in solid form until it decays into innocuous isotopes (e.g. [17]). This requires immobilization on timescales long with respect to ⁹⁰Sr’s half-life of 28.9 years. Laboratory (e.g. [18,19]) and modelling [20] studies indicate strong potential, and the technology has been considered for treatment at the US Department of Energy Hanford Site [21,22].

Successful water management and power generation around the world hinge largely on the retention and flow control of water in reservoirs and canals. In CA, USA alone more than 5000 km of levees and 1200 dams exist [23]. Construction quality ranges from fully to non-engineered, and their remediation is practically and fiscally prohibitive with conventional techniques. Yet, dam and levee breaches are often catastrophic to the society (e.g. Jones Tract, CA [24], Hurricane

Figure 1. (a) Proposed Great Wall Sahara treatment [7] and (b) desert encroachment towards Nouakchott, Mauritania.

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A multi-functional design that persists over generational timescales is the ultimate sustainable objective as the underlying biogeochemical processes are common among many applications. This represents a step change in how broad civil engineering problems are characterized and solutions are developed. A multi-functional application should seek to address multiple site-specific and regional environmental, infrastructure and agricultural demands and issues. A conceptual example for a motorway embankment is shown in figure 3. Using soil engineering in vivo, the soil embankment could become a multi-functional infrastructure component, simultaneously (i) reinforcing soils by biocementing using bacteria to generate mineral precipitates that support the roadway, railway and slope; (ii) stabilizing surface soils with plants to increase slope stability and minimize surface erosion; (iii) controlling surface and ground water flow by manipulating hydrogeological properties of soils (increase by biomineral dissolution and decrease by bio-clogging); (iv) decontaminating surface water infiltrating the soil by bioremediation; and (v) capturing carbon dioxide by in situ inorganic precipitation of carbonate minerals.

3. MULTI-FUNCTIONAL SYSTEMS: A FRAMEWORK FOR SOIL ENGINEERING IN VIVO...

Soil engineering in vivo uses biogeochemistry (a combination of chemical reaction networks and biological processes) within the soil habitat. It also requires continuous process monitoring of this living system and upscaling to develop full-scale implementation procedures. The inter-relationship and interplay between these different components are presented separately for clarity in the schematic in figure 4 and subsequently, although they are highly interdependent.

3.1. Biogeochemistry: chemical reaction networks and biological systems and processes

The biogeochemical framework for soil engineering in its broadest sense here, is directly taken from the current approaches used in bioremediation engineering; outlined in this section (e.g. [49]). The chemical reaction network and the biological systems and processes are inextricably linked in the near surface (≤25 m), and herein are considered holistically as biogeochemistry [50]. Geochemical processes are driven by reactions between the elements that comprise soil organic matter, minerals, gases and solutes. One dominant condition for chemical reactions is the redox gradient that exists between the atmospheric O_2(g) pool and its depletion in the subsurface owing to the influx and microbial decomposition of organic matter from the above-ground biomass [51]. When anoxia occurs below the depth of O_2 penetration, anaerobic processes degrade organic material, whereby respiration occurs using terminal electron acceptors other than O_2; notably, nitrate, higher valent manganese and iron minerals and sulphate [52]. Because hydrogen ion
transfers accompany electron transfers to maintain charge balance in aqueous soil solutions, oxic environments (shallower) are relatively more acidic than where anaerobic processes dominate (deeper zones; [51]). Conversely, microbial respiration in these deeper strata—based on nitrate, sulphate and oxidized iron or manganese—produces net alkalinity [53]. A further condition driving chemical reactions is the inherent free energy of the parent material from rock mass, which formed under geological conditions of higher temperature and pressure than the ambient soil environment. Because most parent material is made up of complex silicate oxide minerals, their chemical decomposition to solutes and secondary minerals (e.g. clays) consumes hydrogen ions, thus contributing to the subsurface alkalinity.

The electron and hydrogen ion transfers between the various element pools control the master variables of

Figure 3. Schematic of multi-function solution using ‘soil engineering in vivo’.  

Figure 4. Framework for generalized approach to ‘soil engineering in vivo’. 
pH and redox status. These dictate the chemical form of many metal compounds, whether dissolved, sorbed or precipitated, and thus determine their bioavailability, mechanisms of toxicity, and transport and mobility within the hydrologic cycle [54]. Furthermore, pH and redox status are major controls on rates of abiotic chemical reactions and set physiological limits for the soil as a habitat for microbial growth and activity. This is with respect to microbial ecosystem dynamics and associated microbial transformations of major and trace elements and organic contaminants [55,56].

3.2. Soil habitat

The inherent complexity of soil deposits is because of the deposition and erosion of mineralogically complex parent material under natural transport processes, also the chemical complexity of soil organic matter, the largely unknown gene pool and physiology of the indigenous microbial populations, and their continuous interaction and dynamic evolution. Herein, the term ‘soil habitat’ is comprehensive, including the soil particle matrix, its mineralogy and associated microbial populations and the pore fluids and their composition. Critical attributes are wide-ranging for each component. For the soil matrix, important attributes include spatial variability, soil particle and aggregate size distribution, particle shape, mineral chemistry and surface charge, organic carbon characteristics and microscopic (immobile domain) porosity, as well as sessile microbial populations, and so on. For the pore fluid(s), important attributes are the physical properties governing flow such as density, viscosity, temperature, surface tension and pressure, as well as the attributes governing biogeochemical transformations (e.g. chemical composition, planktonic bacterial populations, suspended colloidal phases). Pore gas attributes include composition, pressure, temperature, and other physical and chemical characteristics. Pore gas may serve as a useful vehicle for controlling/removing volatile non-aqueous phases (via soil–vapour extraction schemes for instance), or in conveying water in vapour phase in desert environments. However, these complex and varied phenomena are often glossed over or ignored when considering saturated (ground water) zone manipulations and engineering, due in large part to the challenges in characterizing the subsurface variability, especially the microbial populations either naturally occurring (e.g. [57]) or under engineering control strategies (e.g. [58]).

3.3. Compatibility of systems

Manipulation of a specific biogeochemical pathway (e.g. by amendment of soil with nutrients, other chemicals and biota such as plant crops and potentially microbes) for a desired outcome (e.g. calcite precipitation) can require/force a shift in the ambient environment. Physical and biogeochemical compatibility of the treatment with the ambient environment must be considered.

Physical compatibility is necessary for delivery of nutrients and/or biota uniformly throughout the subsurface. Identification of the limits of treatment effectiveness can be identified considering micro-organism size, pore throat size within the soil matrix, ambient stress conditions and treatment objective [30,48,59,60]. As shown in figure 5, micro-organisms may be motile and unaffected by ambient stress conditions in soils with particle sizes larger than about 2 μm. However, in smaller particle soils, the micro-organisms are probably trapped with diffusive nutrient transport becoming increasingly important [60].

Competition among other natural biological species must be similarly examined when nutrients, other chemicals or new organisms are added to create a dominant biogeochemical pathway. In the natural environment, nutrients added for biostimulation are available to all systems, requiring the desired system to out-compete competitors and create an advantageous environment that must be sustained throughout a treatment process. Such competition among microbial guilds capable of mediating redox reactions with distinct (and respective per guild) electron-accepting chemical compounds is well established (e.g. [61]). Additionally, the role of protists as predators of subsurface microbial species (e.g. [62]) within the context of engineering stimulation of native species is not well studied or observed.

3.4. Process monitoring

Integration of biogeochemical processes within soil requires continuous process monitoring of system indicators throughout the project service life. Markers to track the (in)equilibrium of the chemical reaction network and condition of the biological processes are well-documented in the bioremediation literature [52,63,64]. Shallow subsurface microbial communities capable of using distinct electron acceptors, often generate a ‘redox-spectrum’ along a flow path conveying nutrients sufficient for activity (e.g. along a contaminant plume path). The redox-spectrum appears as a continuous decrease in measured or theoretical electrochemical potential (see [52]) along the flow path, associated with sequential exhaustion of electron-accepting chemical compounds in the order of oxygen, nitrate, iron and manganese minerals, and sulphate. For the particular case of calcite precipitation, urea and its degradation product ammonium(um/a) can serve as indicators of reaction extent for this kinetically controlled reaction. Finally, the precipitation/dissolution potential for calcite is classically indicated by the saturation index. This parameter is zero when calcite is in equilibrium with the ground water; however, disequilibrium is often observed and can arise from and indicate incomplete mixing, lack of nucleation sites, pore-scale variation in pH, among other factors. Critical markers for soil processes depend on the application objective. Monitoring of chemical concentration in ground water provides direct assessment of water quality while nucleic acid-based analyses determine genetic and functional microbial diversity and measures of soil strength provide direct measures of improvement to mechanical soil properties.

In general, monitoring processes are either direct or indirect. Direct measurements typically are established, accurate and accepted standards that require discrete
physical samples extracted from the subsurface, resulting in time-delayed measurements. Indirect measurements (e.g. electrical, magnetic and geophysical measurements) that provide real-time volume-averaged secondary indicator measurements are increasingly common \[65,66\]. The two methods are often used in tandem, with indirect measurements providing real-time monitoring and direct measurement providing occasional reference/calibration/verification data. It seems likely that with the development of bioengineered solutions, new approaches to monitoring will be developed, particularly expanding the use of biological activity beyond current bioremediation applications as a broader marker for soil engineering functions.

3.5. Upscaling for field application

Communal knowledge drops precipitously as processes are upscaled, and as a result upsizing is the most challenging issue for many soil engineering systems being researched. Upscaling approaches are multi-faceted, but often lead with experimental approaches enhanced by analytical and numerical work. Convention builds on examination of a biogeochemical process under stringent controlled conditions (i.e. sterile environment with select bacteria species and chemical/nutrients), and then relaxation of the conditions as it is applied to zero-dimensional batch reactors, one-dimensional soil columns, two-dimensional bench models, and then three-dimensional prototypes and full-scale pilot application. Monitoring complexity increases factorially with the increase in experimental variables. Modelling also parallels this increase in complexity, beginning with analytical modelling of specific biogeochemical variables in controlled batch or column systems, and then using biogeochemical codes linked with higher dimension flow and transport-simulation capabilities (e.g. TOUGHREACT, STOMP; see \[56\]) to simulate in situ conditions.

Upscaling towards in situ conditions with less control and observability involves a loss of information that changes the nature of the problem \[67\]. This is acutely

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Figure 5. Overview of compatibility regimes considering particle size and ambient stress conditions (Rebata-Landa & Santamarina 2006. ©Copyright 2006 American Geophysical Union. Adapted from American Geophysical Union).
demonstrated with heterogeneities in the velocity and concentration fields (due to non-uniform boundary conditions, stratigraphic spatial variability, subsurface reaction properties), which can produce complex solute distributions with sharp gradients and preferential flow and transport pathways [68]. These gradients are difficult to detect and yet can be a primary control on biogeochemical transformations. This has led to upscaling techniques that focus on Lagrangean measures (e.g. travel-time, cumulative reactivity) instead of conventional (Eulerian) plume delineation (e.g. [69]).

4. EMERGING TECHNOLOGY EXAMPLE: MICROBIALLY INDUCED CALCITE PRECIPITATION

One emerging process that holds promise for multifunctional sustainable applications is the biogeochemical process of carbonate precipitation. Microbially induced calcite precipitation (MICP) has many potential applications, including improvements to mechanical (e.g. strength, liquefaction resistance, stiffness) and hydraulic (e.g. reduction in permeability) soil properties, immobilization of heavy metals (e.g. 90Sr and others) in the subsurface, and sequestration of contaminants and byproducts (e.g. [69]). MICP has been previously explored for microbially enhanced oil recovery [70,71] and builds on prior research on chemically induced calcite precipitation [72,73]. The details of this process are relatively well understood and although many scientific issues remain challenging to quantify, upscaling to field deployment has nearly arrived. This technology is presented herein to exemplify the framework and approach proposed above (figure 4).

4.1. Enabling biogeochemical processes

MICP occurs following [41]:

\[
\text{Ca}^2^+ + 2\text{HCO}_3^- + \text{OH}^- \rightarrow \text{CaCO}_3 \downarrow + \text{H}_2\text{O}, \quad (4.1)
\]

\[
\text{Ca}^2^+ + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 \downarrow + \text{CO}_2 + \text{H}_2\text{O}. \quad (4.2)
\]

The creation of calcium carbonate (calcite) occurs as a consequence of bacterial metabolic activity. When the rates of urea hydrolysis and calcite precipitation are equal, such that NH\textsubscript{4}\textsuperscript{+} cations effectively replace precipitating Ca\textsuperscript{2+} cations then the pH remains neutral [74]. When urea hydrolysis outpaces calcite precipitation, the pH of the proximal environment increases (e.g. [75]). Calcite precipitation may be achieved by many different processes [59], including urea hydrolysis, denitrification [76–78], sulphate reduction ([79], inducing dolomite precipitation) and iron reduction ([80], inducing ankerite and other mixed mineral precipitation). Enzymatic hydrolysis of urea by microbes is the most energy-efficient [59], and urease activity is found in a wide range of micro-organisms and plants [81]. Selection of the process ultimately implemented in the field should consider the differences in efficiency rates, contaminant byproducts and energy consumption between these processes. Bacillus pasteurii (American Type Culture Collection (ATCC) 6453) and a more recent strain, Sporosarcina pasteurii (ATCC 11859), an alkalophilic bacterium with a highly active urease enzyme [46], have been used in laboratory studies.

4.2. Systems compatibility

Effective treatment with MICP depends on the compatibility between groups of soil components, examples of which are highlighted herein. Geometric compatibility between the microbe size (S. pasteurii are rod-shaped and approx. 1 \(\mu\)m in diameter and approx. 3–5 \(\mu\)m in length) and the soil structure pore size is necessary for delivery of micro-organisms for uniform treatment. Data have shown MICP treatment to be effective for soils with particle sizes of about 25 \(\mu\)m diameter (silty soils) and larger [31,82]. Biochemical compatibility is critical for controlling the rate and timing at which MICP occurs, and porewater compositions affect this. MICP increases in efficiency (assessed in terms of the rate at which soil stiffness increases during treatment) as the ground water salinity increases towards an ocean-water composition [82]. The initiation of precipitation is determined by treatment solution buffering, and appropriate proportions of ammonium chloride and sodium bicarbonate can control the onset of precipitation [83]. Soil particle mineralogy and surface characteristics also affect MICP. Calcium, silica and iron base mineral sands can all be effectively treated [82]. All natural sands (and silts) tested that are geometrically (size) comparable show improvements in soil stiffness with sufficient time.

4.3. Process monitoring of experiments

MICP process monitoring is exemplified through results from one-dimensional column experiments (length = 45 cm, diameter = 5 cm) performed on sand (\(D_{50} = 0.21\) mm) to improve spatial uniformity (figure 6a) [84]. Similar approaches have been reported by Whiffin et al. [85]. The data obtained were indirect real-time measurements (e.g. pH, versus, optical density) and more accurate, time-delayed direct measurements (chemical concentrations, bacterial plate counts) from four column elevations throughout treatment. Following injection and throughout treatment, optical density (indirect) and plate counts (direct for viable cells) were performed on biotic samples to assess bacterial distribution (figure 6b). Calcite precipitation at particle–particle contacts was monitored in real time as changes in soil stiffness with (indirect) geophysical shear wave velocity measurements [86,87] (figure 6c). The shear wave velocity (normalized by the initial shear wave velocity at each monitoring point) increased at all measurement locations throughout treatment (figure 6c). Post-test measurements of precipitated calcite (direct) validate geophysical measurements of changes in soil stiffness (figure 6d).

4.4. Parallel modelling of experiments

Biogeochemical modelling of experimental MICP work at the batch-scale has confirmed the conceptual model underlying the general reaction network and its
behaviour, and is enabling scoping assessment of more complex systems. Building on previous MICP analysis (e.g. [17, 88]), the MICP reaction network was incorporated into the modelling framework TOUGHREACT [89–91], a multi-phase, multi-component, reactive transport model [84]. The minteq.v4.dat thermodynamic database [92] and the kinetic expression for jack bean (*Canavalia ensiformis*)-derived enzymatic ureolysis [93] were adopted. Urease was simulated as an immobile species, and the spatial urease distribution was modelled as a log-linear relationship for biocolloid advection and filtration through an inverse solution using UCODE [94]. Even with these limitations, insights can be gained. Very good agreement in the spatial distribution of calcite is obtained by the model. With precipitated calcite concentration serving as a proxy for soil stiffness (as the relationship between the two is proportional; [95]), good agreement is also obtained in trends of shear wave velocity (soil stiffness) throughout the treatment process at all sampling locations along the test column (figure 6c,d).

### 5. EXPERIMENTS AND MODELLING AT SEPARATE SCALES

To date, MICP research has focused on centimetre and metre length scales under zero-delayed (batch) and one-dimensional (column) experiments. Insights gained at these laboratory scales are critical for full-scale implementation.
5.1. μm: Calcite crystal structure, microbial embedment

Scanning electron microscopy (SEM), laser-scanning confocal microscopy and energy-dispersive X-ray spectroscopy have revealed characteristics of the calcite crystal structure and the role of micro-organisms. SEM images have captured microbial ‘beds’ within the calcite structure, verifying that micro-organisms create local environmental changes so that cells serve as preferential calcite nucleation sites (figure 7a). Variations of the soil type and treatment formulation also alter the calcite structure; the conventional treatment formula ([15,48,75]) produces a random amorphous calcite structure.

5.2. mm: Particle–particle cementation and degradation, spatial calcite distribution

SEM and X-ray computed tomography (CT) at the particle level capture the spatial distribution of calcite. MICP has apparent preference towards particle–particle contacts owing to bacterial filtration and greater access to nutrients available in the flowing pore fluid (figure 7b,c). Calcite crystal thicknesses on exposed particle surfaces are less than approximately 10 μm, while structures at particle–particle contacts is much higher for saturated sands. Unsaturated sands treated by percolation results in calcite precipitation almost exclusively at particle contacts. Degradation of particle–particle contacts typically occurs through the calcite structure and not at the calcite–silica interface. Three-dimensional views from CT scanning confirm SEM observations and reveal that the pore structure remains connected after treatment (figure 7d) [59].

5.3. cm: Improvements to engineering properties, monitoring technique developments

Element test results on MICP-treated sand have revealed the potential improvement to engineering, mechanical and hydraulic properties and enabled the development of real-time monitoring techniques (figure 7e). MICP treatment can reduce hydraulic conductivity [46,85], increase stiffness such that loose sand becomes soft rock [59,77,78] and alter volumetric behaviour [59]. The universality of MICP has been examined using different soil gradations, mineralogies and ground water conditions. These tests have also enabled improvement of geophysical measurements [95–97] and discrete sampling protocols necessary at larger length scales.

5.4. dm: One-dimensional columns for treatment uniformity, bench-scale models assessing improved geosystem performance

Extension of element specimens in one-dimensional (figure 7f) to multi-dimensional models (figure 7g) enables treatment optimization and insight at the 1-G model scale of how geosystem performance (e.g. foundations) may be improved with MICP. MICP has been successfully implemented in one-dimensional columns to a distance of 5 m [85], and shorter 0.5 m one-dimensional columns have been used to improve...
the timing, rate and uniformity of MICP treatment (per above data [84]), Martinez & DeJong [44] demonstrated using 1-G model tests that the capacity of shallow foundations could be increased fivefold or more through cementation of near-surface sands.

5.5. m and km: Three-dimensional test chambers, centrifuge modelling and field scale treatment

Initial results are now being generated for three-dimensional test chambers and field conditions. Centrifuge modelling is being implemented to assess the performance of MICP-treated soil and supported structures when subjected to dynamic earthquake loading. Following successful treatment of 1 m³ soil, treatment of a 100 m³ soil specimen has been performed (figure 7i) [77,78].

Limited progress has been made in upscaling MICP process models for general use, in part, as a result of the strong and complex coupling among flow, mixing and reaction (e.g. [98]). However, for particular engineering applications at field-scale, research at all length scales continues as improved scientific understanding is continually sought. Specific challenges and issues that remain include precise understanding and modelling of bacterial distributions in the natural subsurface and associated ureolysis rates, exploration of alternative processes such as denitrification, mapping subsurface stratigraphy, flow and transport through heterogeneous media, durability and permanence of treatment, and biodiversity and behaviour in nutrient-limited environments.

The primary research mindset and focus has been on single function applications (with different research groups around the world examining MICP for different applications). The multi-function application proposed herein requires additional scientific and engineering research before the performance of MICP can be predicted and executed in the complex natural environment.

6. MULTI-FUNCTIONAL SOLUTIONS FROM FIRST PRINCIPLES: CHALLENGES AHEAD

Multi-functional solutions (e.g. figure 3) using MICP in combination with other processes cannot be realized using empirically based and conservative design methods; a step change in our design approach, wherein analysis of these complex systems based on first principles is needed. In the nineteenth century, structural engineers began designing based on the first principles of solid mechanics. In the twentieth century, water treatment engineering incorporated aqueous chemistry in an analogous manner [99]. The interface of the twenty-first century is between biology and civil and environmental engineering, and requires a similar step change in theoretical concepts for application, engineering analysis and design principles.

It is daunting to consider the application of biogeochemical engineering processes in natural environments. Some of the key biological challenges, for example, are the predominance of unknown genotype and phenotype in the subsurface, and the complexity of indigenous microbial consortia and their ecological function. Fluid movement and mass transport pathways depend on spatially variable physical properties, such as permeability that are not easily mapped from the surface. Lithological structures yield spatially variable mineralogy with attendant differences in mineral surface hydrophobicity, charge, chemical bonding environment and trace element provenance for organisms.

Spatial variability is critical for biological processes. Biota respond to the physical and chemical environment, and ecosystem dynamics are influenced by the temporal variability of flow and transport within a spatially variable environment. Microbial function is dominated by attached growth communities in the subsurface, and the spatially variable mineralogy is likely to exert strong selective pressure and impact community structure and function. A key task will be to understand how different biological processes interact. For example, soil stabilized with MICP is likely to be covered with vegetation. It will be important to establish that activity at the root scale has a synergistic (and not antagonistic) effect on MICP. The ability of mycorrhizae associated with plant roots to release organic acids that result in mineral dissolution underscore these concerns. Such considerations will be novel challenges to engineers who may presently be comfortable with designing structures of concrete and steel, which are assumed to be spatially and temporally invariant with respect to material parameters.

These challenges are evident in the current engineering practice for harnessing subsurface biological processes (e.g. land and ground water remediation). Extensive site-specific data are required to infer, for example, solute transport and biodegradation rates. Current advances in computational methods and site investigation allow numerical models to consider a great deal of this complexity; on a computational scale which approaches that of, for example, climate simulations [63]. However, predictions obtained are largely based on simple extrapolation of prior results from laboratory/bench scales to larger length and timescales. This extrapolation can be fraught with problems as, for example, highly localized mixing-limiting processes at the micro-scale are captured in equivocal volume-averaged models that mask critical process-limiting factors (e.g. [100]). Further, little is known about how the system will evolve spatially and temporally, and there is no fundamental approach that provides parameter values for desktop analysis prior to expensive, site-specific engineering investigation.

To address these challenges, it is necessary to establish the theoretical framework and tools to assess the subsurface biogeochemical-soil habitat and the subsurface spatial variability of the respective components. This framework must then be applied to research experimental design, to target the hypotheses drawn from the above challenges, target data acquisition to address these specific challenges and develop improved methods for
in situ observation. This begins to point to a research agenda to develop analysis and design methods that are based on first principles: (i) sound biological theory; (ii) hypothesis-driven field experimentation; and (iii) new sensing methods that are preferably non-invasive and non-destructive.

7. SUSTAINABILITY: COMPREHENSIVE DESIGN CRITERIA

Multi-functional solutions based on first principles will be evaluated against the broader social criterion that is emerging. In the twentieth century, energy-intensive physical practices (e.g. cement manufacturing, ex situ soil remediation, strip mining, and so on) continued for decades owing to perceived abundance of natural resources and unawareness of the consequences. Today, it is clear that the resources are finite and the impact and costs of past consumption are compounding (e.g. [101,102]).

The twenty-first century will be characterized as the era of sustainability [103]. The historical project assessment based solely on financial investment is incomplete. Projects must now be evaluated against the social obligation we have to limit environmental impact, an holistic assessment of energy embodied in the project, the project’s carbon and water footprint, the probabilities of failure and rebuilding throughout the project service life, and the ability for material and site reuse for future generations [104,105].

8. INSTITUTIONAL CHALLENGES: REFORMATION IS NECESSARY

Realization of these multi-functional solutions in society necessitates a step change in the culture and ethos of research, education and policy.

8.1. Research reform

This research is inherently interdisciplinary; scientists and engineers must become intertwined. Change is required at the individual and institutional levels. Scientists must move towards more proactive engagement, control and manipulation of biological process so that biological processes can be reliably harnessed in engineering applications. Simultaneously, engineers must consider soil (and the systems built upon it) as living ecosystems. The mindset of once-and-done design and construction must be transformed into continuous performance monitoring of infrastructure. Fortuitously, health monitoring of infrastructure (e.g. [106–108]), which is becoming more widely accepted, is the first step. At the institutional level, this new research may not be amenable to the conventional organization and culture in which specialties such as civil engineering remain compartmentalized. Interdisciplinary entities/groups within which ideas can be generated, vetted, proofed, explored and developed freely are necessary. The culture of these groups and the broader institution must value these activities.

8.2. Education reform

The growth and maturation of this new field over the coming decades require development of new engineers and scientists. Education—and (post-) graduate education in particular—in the latter part of the twentieth century that focused on individuals developing expertise in a single niche area is insufficient for this interdisciplinary field. Individuals must have expertise (core competency) in a certain area(s), but must be knowledgeable and able to communicate across several different disciplines [59]. In essence, a seventeenth century type renaissance education model is necessary. Creativity, innovation, mind experiments and critical thinking at the systems level must be emphasized. Fortunately, new education modules such as interdisciplinary seminar series, interdisciplinary (co-taught) courses, interdisciplinary graduate programmes and graduate programmes requiring a minor in another discipline, science/engineering/business combined with Master’s degrees, and doctoral training degrees (interdisciplinary coursework only degree) are emerging [28].

8.3. Industry and government restructuring

The movement towards sustainable performance-based design and the associated changes beginning in construction policies and practice must continue. Cost assessment must be expanded beyond the physical footprint and construction cost to include life-cycle analysis of all components, ranging from the manufacturing of raw materials through to site re-use feasibility after the service life expires. This may also require government subsidies/credits (similar to that currently being given for renewable energy sources) as a comprehensive sustainable assessment (cradle to grave) of materials and construction may (or will likely) lead to a final design that is more expensive when analysed under the current costing/bidding framework. This may lead to government subsidies for private projects and the
restructuring of public work projects, where the design selection criteria could be changed/modified to require/endorse consideration of a broader set of factors in a sustainable framework.

9. CONCLUSIONS

Society’s major civil and environmental challenges cannot be solved using the intensive energy twentieth century treatment solutions. New sustainable solutions are needed. It is proposed herein that ‘soil engineering in vivo’, an emerging interdisciplinary approach which recognizes soil as a living, active system that has the capacity to provide sustainable solutions, may be one of them.

The envisioned applications are many and wide-ranging, from anti-desertification measures for northern Africa to reducing the liquefaction settlement for a foundation building. To date, applications investigated are largely single function solutions, but herein it is proposed that select biogeochemical systems can simultaneously provide multi-functional solutions.

Multi-functional solutions must consider the processes occurring within soil systems both independently and in a coupled context. Techniques for real-time monitoring of these integrative solutions are critical. Upscaling requires extensive experimental work that is hypothesis-driven owing to the inherent complexity of natural systems. The experimental work must be complemented by rigorous analytical and numerical modelling to identify the first-order principles controlling the system.

MICP has rapidly matured towards field implementation, with potential applications including improvements to mechanical and hydraulic soil properties, immobilization of heavy metals and sequestration of atmospheric carbon. Experimental and numerical modelling, including real-time process monitoring, have provided significant advances in understanding and control of MICP at all length scales.

Realization of MICP and similar processes as field-scale multi-functional solutions requires a step change in how science and engineering is performed, and must meet the emerging sustainability criterion. Significant additional research and development is needed in order to provide solutions within the natural environmental that are based on first principles. The primary challenges in this area include assessment of subsurface ecosystems and their interaction with the available fluids and minerals, and mapping and modelling of subsurface variability of pore structure, mineralogy, ground water flow and transport, and bacterial diversity.

Finally, realization of these multi-functional solutions in society necessitates a step change in the culture and ethos of research, education and policy. Interdisciplinary research requires greater interaction between scientists and engineers, formation of interdisciplinary work groups and departments, and institutional embrace of disciplinary work. Maturation of this field requires a new generation of scientist and engineers with a ‘renaissance type’ education equipped to use their own expertise and leverage the knowledge in interdisciplinary teams. Industry and government reform is needed to fund the development of new solutions, and incentives and evaluation criteria that encourage their deployment through industry should be developed.

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