SmartSoils, Adaptation of soil properties on demand
SmartSoils, Adaptation des propriétés de sol à la demande

W.O. Molendijk
Deltares, Delft, Netherlands
W.H. van der Zon
Deltares, Delft (Since Februari 2008: Vopak, Rotterdam), Netherlands
G.A.M. van Meurs
Deltares, Delft, Netherlands

ABSTRACT
In 2003, Deltares (previously GeoDelft) launched the concept of SmartSoils®. The potential of enhancement and control of various natural geological processes in soils by microbiological means was discovered essentially by realizing what microbiological research and development has achieved in agriculture, nutrition, medicine and electronics. Where natural calcareous sandstones need thousands of years for their diagenesis, SmartSoils techniques like BioGrout applied on loose sand, only take days to convert it into sandstone with an unconfined compressive strength of up to 35 MPa. Consequently, the basis was laid for a paradigm shift in geo-engineering. In civil engineering, ordering the desired properties of concrete and steel are common practice for decades. With SmartSoils techniques, the mechanical and hydrological soil properties can now also be adapted in-situ to meet engineering requirements. BioGrout adapts the strength and stiffness of sand without reducing its permeability significantly. Therefore, it opens new perspectives for the reduction of (soil) liquefaction and the upgrading of existing foundations. BioSealing, another SmartSoils technique, can stop groundwater leakage in various civil engineering constructions or under natural circumstances like saline water seepage in a polder. Sealing is realized without the need to know the exact location of the actual leak in advance. BioPeat, as a last example, diminishes oxidation of peat and improves its strength and therefore it may enable shallow underground constructions. Research in the field of SmartSoils has lead to several spin offs; like research for application in the mining industry, architecture and many more fields.

RÉSUMÉ
En 2003, Deltares (précédemment GeoDelft) a lancé le concept de SmartSoils®. Exploitant les efforts énormes de recherches en microbiologie disponibles dans la littérature pour application dans l'agriculture, l'alimentaire, la médecine et l'électronique, le potentiel d'amélioration de toutes sortes de processus géologiques naturels a été découvert. Là où les grès calcaires naturels ont besoin de milliers d'années pour leur genèse, les techniques de SmartSoils comme BioGrout, appliquées au sable nécessitent seulement quelques jours pour le convertir en grès. Sa résistance peut alors atteindre jusqu'à 35 MPa. En conséquence, on peut entrevoir un changement profond dans la manière d'appréhender les problèmes de génie civil. Pour les travaux de génie civil, les propriétés du béton et de l'acier peuvent être spécifiées lors de leur fabrication. Maintenant, les propriétés mécaniques et hydrologiques de sol peuvent être adaptées in-situ pour répondre aux exigences de construction. BioGrout peut être appliqué pour adapter les propriétés de résistance et de rigidité des sables sans en réduire la perméabilité, et ouvre donc de nouvelles perspectives pour la réduction des problèmes potentiels de liquéfaction et l'amélioration de fondations existantes. BioSealing, une autre technique de SmartSoils, peut colmater des fuites d'eaux souterraines dans tous types de constructions de génie civil, ou des circonstances naturelles, comme les infiltrations dans les zones de polders, sans avoir besoin de localiser précisément la fuite à l'avance. BioPeat, comme dernier exemple, peut en grande partie arrêter l'oxydation de la tourbe et la renforcer, afin de permettre la réalisation de constructions souterraines peu profondes. La recherche dans le domaine de SmartSoils a aussi pu être appliquée dans l'industrie minière, l'architecture et beaucoup d'autres domaines.

Keywords : bio-geo-engineering, ground improvement, stabilization, MICP, bacteria, micro-organism, sustainable.

1 INTRODUCTION

In 2003, Deltares (previously GeoDelft) launched the concept of SmartSoils®: engineering soil properties 'on demand'. In the years before, a newspaper article of a new soil improvement technique based on plant enzyme utilization (Kucharski et al., 1996, 2002), lead to an Australian PhD student (Whiffin, 2004) who tried to renovate sandstone monuments using bacteria. Through these Australian contacts, we came across some papers that described the role micro-organisms play in the natural genesis of soils and rock (Boquet et al., 1973; Castanier et al., 1999).

At first sight the possibility of microbial soil improvement sounded rather remote for civil engineers, however a small group of people got inspired. What started of as a kind of hobby became more serious after a bag of sand sent to Australia, was returned as a column of solidified sand, resembling calcareous sandstone. The bio-cemented sample, later named BioGrout, was extensively tested and one of the properties that caught the attention was the minor reduction in permeability, while it had gained an unconfined compressive strength (UCS) of several MPa. This is a unique advantage compared to traditional (chemical) grout injections where all pores are stuffed with cement, polymer gel or resin (Karol, 2003). In contrast to existing techniques, the preservation of permeability enables multiple treatments, the use of low injection pressures and obtaining a larger treated volume per injection point. BioGrout enables in situ treatment of soils underneath existing buildings and infrastructure without disturbance of their exploitation.

Some years before the start of the (r)evolution of BioGrout, search of an alternative method to treat a leaking tunnel, lead to notice the role that micro-organisms play in the clogging of water extraction wells. The question was raised whether this undesired clogging effect in wells could be used to our advantage, namely to clog leakages through geo-membranes or sheet pile walls retaining an excavation.

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A set of laboratory experiments was setup. They proved that enhanced microbial activity in a soil column could indeed clog a leakage. These lab experiments were repeated successfully at full scale using perforated sea containers representing small sheet pile supported excavations (Veenbergen et al., 2005). Herewith, BioSealing started, and again, a microbial driven treatment proved to be effective for cases in which the exact location of the leakage cannot be detected or reached by traditional grout injection.

The pioneers realized that bio-mediated ground treatment might become a game changer: soil properties individually adjusted on demand, on site and in-situ adaptation at micro scale meeting engineering requirements at macro scale. Every brainstorm with colleagues, contractors or end-users resulted in more ideas for potential applications. It was time to transform this unconventional idea into a serious research programme.

Apparently, the time was right to start exploring the vast amount of knowledge available in the field of biotechnology. In the following years, comparable initiatives to SmartSoils were started at various universities (see for example DeJong et al., 2009) and research centres and bio-geo-materials became a topic on the European Seventh Framework research agenda. SmartSoils now opens up perspectives for sustainable ground improvement, being far less disruptive with regard to the existing soil structure. Various ground properties can be adapted individually, for example; strength can be set without disturbing natural groundwater flow.

2 PHENOMENA DOMINATING SMARTSOILS

Adaptation of soil properties makes use of phenomena known from microbiology, geochemistry and geo-engineering. In essence, micro-organisms create circumstances in which geochemical reactions take place inside the pores or fissures of soil/rock. The reactions on micro scale generate a change in (geotechnical) properties on a macro scale.

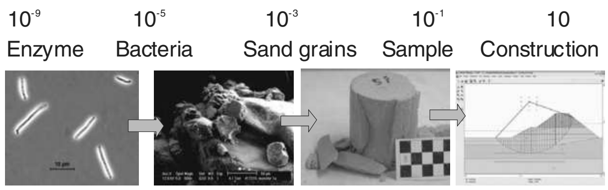

Figure 1: Adaptation a micro scale to obtain effect at macro scale (m)

For example first, ex situ, under aerobic circumstances, the micro-organism *Sporosarcina Pasteurii* is cultivated. Subsequently, the bacterial suspension is injected into the soil, followed by a solution of calcium salt and urea. In the subsurface, the urease enzyme of the microorganism catalyses hydrolysis of urea. The result is precipitation of crystalline calcium carbonate due to the supersaturation of produced carbonate (CO_3^{2-}) and calcium ions. The effect of this precipitation at the granular contacts is an increase of the strength and stiffness of the soil (BioGrout). As a by-product, in this first generation BioGrout process, also ammonium (NH_4^+) is produced.

Based on local regulations, for some applications this ammonium needs to be removed from the subsoil. Therefore, we set out to identify alternative biological processes, which make use of local microbial communities and/or end up with the precipitation of another inorganic mineral. Alternative biological processes are denitrification, iron reduction and sulphate reduction (DeJong et al., 2009).

Precipitation of calcium carbonate takes place as well as the generation of nitrogen gas within the denitrification based BioGrout process (van Paassen et al., 2008). Precipitation of siderite takes place under conditions of iron reduction. This phenomenon is observed whenever iron objects are present in the subsoil, such as iron archaeological artefacts in soil (Neff et al., 2006) and iron sheet piles (van Meurs et al., 2006).

Beside strength and stiffness adaptation of soils, it also is possible to reduce permeability of granular soils and rock fissures (Lambert et al., 2005). In this process, nutrients are injected thus stimulating local micro-organisms to grow. This triggers several processes which have an influence on the clogging mechanism: A bacterial slime, EPS (extracellular polymeric substances) or a biofilm, is formed and due to an increase in acidity, feldspar minerals and clay particles that are present at the grain surface, will be eroded. Released in the groundwater, these particles act like a colloid. Groundwater and bacteria transport the colloid towards the leak. At the location of the leak, flow converges and the colloids are expected to be entrapped in the EPS/biofilm, thus causing clogging in pore throats. Consequently, the permeability decreases one or more orders of magnitude (BioSealing).

Figure 2: Injection of nutrients for BioSealing of saline seepage due to construction of an aquaduct in Haarlemmerringvaart, Netherlands.

However, as bacterial activity has to be stimulated in situ, the response time before a leak is sealed, depends upon the distance between the injection point and the leak. Acceleration of the BioSealing process will extend its applicability to situations where time to reach sealing is the first priority.

The advantage of SmartSoils is that the required circumstances are created in situ, without altering the original stratigraphy and structure (pore scale engineering). Therefore, transport of nutrients and reactive agents is needed towards the location at which the properties need a change. Tests with BioGrout show that this can be realised, not only on a core scale (Whiffin et al, 2005). In addition, precipitation of calcite could be realised at a distance of about five meters from the injection point (Whiffin et al, 2007).

Progress is made regarding the volumes in which the geotechnical properties of stiffness and strength are improved. Stepwise up scaling from 1 litre, via fifty litres and one cubic metre (box test) has resulted in a successful full scale experiment in September 2008. A 40 m^3 block (length: 7 m, width: 3-4 m, height: 1-2 m) was created inside a sand box of 10 * 8 * 3 m^3, using standard injection equipment.

Figure 3: Scale up of the BioGrout: 40 m^3 of Calcareous sandstone.

Precipitation of calcite extended to near the extraction well. Strength (UCS) ranges from 2 to 12 MPa. And, permeability remained practically unchanged (van Paassen et al., 2009).

Not only local soil properties can be adapted within the concept of SmartSoils. In addition, mine tailings and dredged sludge can be adapted. This idea was worked out in the so called ‘sludge mattress’, a light weight material for road foundation (van Ruijven et al., 2005). The sludge mattress is contained in a system such that any possible contamination, attached to the original material and leaching from the mattress is degraded, locally adsorbed or immobilised and then can be removed easily out of the system.

3 OPEN INNOVATION NETWORK

3.1 *Cooperation & Support required*

SmartSoils technologies approach ground improvement differently when compared to traditional techniques like grouting. For potential applications the sky seems the limit. Encountering such an enthusiasm from many colleagues around the world is of course encouraging. It is a requirement to reach a broad market introduction including the status of innovation finally. However, already at the “eureka” moment in 2002 it we realized that a broad support of all key players acting in each step of the innovation cycle (Berkhout, 2000; Barends, 2008) would be required. Therefore, from the very beginning, we started to develop an extensive network around the research.

Universities were important to hook up on specific microbial knowledge at first. However, soon we found out that fundamental knowledge from other disciplines is required to enable modelling and monitoring of the relevant transport and reaction processes. Understanding of the fundamental processes is required to guarantee an environmentally safe application (prevention of unexpected or undesired side effects) and to construct a reliable engineering model.

To enable sound practical applications, the involvement of contractors and industry was of vital importance. Only by their input on project logistics, project risks, view on potential applications, IP protection, project costing etcetera it could be possible to develop a final product (technology enabled) that can be delivered to a client or end-user. Furthermore, feedback of (public) end-users, policy makers, specialists on legislation, opinion leaders and NGO’s is required to facilitate demand and support for such a new, unconventional technology development and related products.

To enable ourselves to manage all these relations and risks, risk management according the RDM method (Keizer et al., 2002) was introduced in the research and development programme.

3.2 *Paradigm shift in Geo-engineering*

Right from the start, it was recognized that bio-mediated soil and rock was likely to give the discipline of geo-engineering a new boost (Barends, 2005; DeJong, 2007; Terbruggen, 2004; Whiffin et al., 2005). Being able to adapt ground properties at a distance 5 to 10 metres away from an injection point (Whiffin et al., 2007) enables the perspective of upgrading foundations of infrastructure, buildings or installations while in operation, without interruption of serviceability. Upgrading of foundations and earthworks enables extension of service life or higher asset utilization. These and many more examples are all typical topics of the Strategic Research Agenda of the European Construction Technology Platform (http://www.ectp.org/documentation.asp). Together with the evolution of bio-mediated ground materials, those have become realistic goals.

Construction in urban environments requires little disturbance of daily life. Currently the city of Amsterdam suffers under the construction of a new metro line. Although being constructed underground, its deep alignment unavoidably creates nuisance and introduces a risk for damage to adjacent, sometimes poorly founded buildings. Recent developments like BioPeat, coating of the organic fibres in peat to gain strength, stiffness and to stop oxidation, open up the perspective to shallow underground construction (Lasseur, 2007). It is expected that bio-mediated soil improvements will give underground construction a boost, as disturbance of the project surroundings is expected to decrease drastically.

3.3 *Adaptation as required for any purpose*

An elegant aspect of bio-mediated ground is the possibility to adjust various geo-engineering parameters individually. Besides its positive effect on injection distances, preservation of permeability while biogrouting sand, decreases the undesired formation of a hydrological barrier that obstructs groundwater flow. Furthermore, this preservation of permeability triggered the petroleum industry to join our research network to develop an environmental friendly sand control method to be applied in oil and gas production wells. (Latil. et al., 2008). On a very different scale, BioGrout has proven to be effective to stabilize coarse gravel deposits, enabling horizontal directional drilling in such ground conditions.

Sand can be transformed into a strong calcareous sandstone using BioGrout. However, for most geotechnical applications, the optimum treatment is just a small increase in strength, rather than creating a rock type material. E.g. just binding some grains per cubic mm is sufficient to prevent liquefaction. Therefore, typical applications are in the field of reduction of damage induced by earthquakes, in enabling deeper extraction of sand (dredging) and/or in allowing for more steep embankments, in prevention of settlement caused by the vibrating installation of sheet piles and in mitigation of excessive maintenance at high speed railway tracks due to a faster (sound) wave propagation in more consolidated soils.

In situations where a higher strength of the sand is required to prevent scour or other forms of erosion of sand, the formation of a very rigid material might introduce erosion even faster just outside the treated area. Again, a mild treatment allows us to better interact with the natural environment.

Nevertheless, there are situations where potential clients like a very rigid strengthening of the sand. The first samples of calcareous sandstone that were produced in our laboratory, stimulated the creative mind of a famous architect. In 2005, he used BioGrout to integrate houses in a natural dune environment and won the ‘Prix de Rome’ (a prestigious Dutch design award). Since 2006, BioGrout samples have been available in the architectural material expositions of Materio and Materia in respectively Paris and Enter, the Netherlands. Following this public attention, an industry producing lime-silicate bricks has joined our research network to investigate the possibility to produce a bio-brick that has a much smaller carbon footprint than the traditional production process based on the production of lime from limestone and an autoclave step to produce the calcium-silicates. Applications in developing countries were suggested, replacing the local erosion sensitive mud bricks. However, brick production is not likely to become economically attractive on a short term.

3.4 *Expanding network*

In parallel with the development of BioGrout and the growing network of scientific and industrial partners, BioSealing nowadays focuses on new applications, apart from the original application to seal water-retaining structures for civil purposes. Where BioSealing also could be applied as a precautionary method during excavation, unfamiliarity with this innovative method has prevented this type of application so far. Nevertheless, a promising application has been found in the world of hydropower suppliers, where many earth fill dams appear to suffer from leakages. There are many documented cases where the installation of water retaining walls, often grout curtains, have been applied that did not solve the problem sufficiently. As BioSealing is able to find the leak itself, it is expected to be a powerful and valuable additional method to gain safety and operational reliability of these dams. A pilot along the Danube at Greifenstein Austria, is currently going on (February 2009) and has raised interest of CEATI members. A group of at least six large energy providers now consider BioSealing as a topic on their common research agenda.

With the introduction of various strong industrial players in our network, also companies specialized in the biotechnologies are willing to contribute to the research. To protect the interest of these industrial partners, several technologies have been patented.

At the scientific side, forces are also bundled. A first UK-US Bio-Geo workshop took place at MIT in spring 2007 (www.sil.ucdavis.edu). In 2008, the first Bio-Geo-Civil Engineering Conference was organized in Delft (www.smartsoils.nl). In 2008, the idea to start a 'Joint Technological Committee on Bio-Geo-Engineering' under the Federation of International Geo-engineering Societies has been suggested. This new JTC may address general topics like the development of regulation and legislation, education, safety issues, that might obstruct the introduction of bio-mediated ground improvement in various countries in the future.

CONCLUSIONS

Innovations often come from the encounter between different sciences. SmartSoils or bio-geo-engineering combines knowledge of microbial and geochemical processes with alteration of mechanical and hydrological ground properties. An overview of the impulse that SmartSoils technology has given to geo-engineering science in general, is presented. Ten years of research and consequential industrial up scaling has uncovered numerous opportunities for adaptation of the engineering approach for complex constructions, building environments and/or ground conditions. Tenacious steps in coupled research and industrial up-scaling, i.e. at least another five to ten years, are required to expose and harvest the full potential of bio-geo-engineering. Due to the highly multi-disciplinary character of bio-geo-engineering, and the many different stakeholders involved, research and industrial up-scaling are best carried out in an international open-innovation network.

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