The 2016 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM16)
Jeju Island, Korea, August 28 ~ September 1, 2016

Geotechnical Engineering for Sustainable Development

Gye-Chun Cho

Professor, Department of Civil Engineering and Environmental Engineering
Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Korea
gyechun@kaist.ac.kr

Abstract. All forms of development impose an inevitable burden on the natural environment. For sustainable development, this burden must be within the self-resilient limits of the natural environment. However, practical implementation of sustainable development is accompanied by great hardship, as is evident from the lukewarm international efforts in reducing carbon emissions for the prevention of global warming. This is because nature conservation and environmental protection, a major keystone in the concept of sustainable development, contends with powerful opponents such as technological convenience and economic validity in the real world. Thus, sustainable development implies the difficult task of achieving both conservation and advancement to engineers in numerous fields. As geotechnical engineering deals with the earth, it can make a great contribution to efficient sustainable development. Best examples are the development of underground space for the next generation and the development of energy with minimum impact on the natural environment. The boundaries of human life are limited to the physical space on earth and are inevitably based on the ground. Hence, the utilization of underground space has the potential of doubling the available space for human use. In addition, the use of conventional fossil fuels are limited by various technological and economic restrictions, whereas the ground is an area of opportunity that can both supply conventional and non-conventional fossil fuels and reduce damages caused by the use of fossil fuels, mainly CO_2.

Keywords: sustainable development; underground space; climate change; energy depletion

1. Introduction

The concept of ‘sustainable development’ was first suggested in the “*Our Common Future*” report published by the UN World Commission on Environment and Development in 1987. Sustainable development can be defined as development that satisfies the needs of the present, without compromising the ability of future generations to meet their own needs, and is embraced as an essential value worldwide. All forms of development impose an inevitable burden on the natural environment. For sustainable development, this burden must be within the self-resilient limit of the natural environment. However, the practical implementation of sustainable development is accompanied by great hardship, as is evident from lukewarm international efforts in reducing carbon emissions for the prevention of global warming. This is due to nature conservation and environmental protection, which are major keystones in the concept of sustainable development, contending with powerful opponents such as technological convenience and economic validity in the real world.

To engineers in numerous fields, sustainable development implies a difficult goal of simultaneously achieving technological convenience and economic validity alongside natural conservation and environmental protection. Best examples of geotechnical engineering for sustainable development are the development of underground space for the next generation and the development of energy with minimum impact on the natural environment. The boundaries of human life are limited to the physical space on earth and are inevitably based on the ground. Hence, the utilization of underground space has the potential of doubling the available space for human use. In addition, the use of conventional fossil fuels is limited by various technological and economic restrictions, whereas the ground is an area of opportunity that can both supply conventional and non-conventional fossil fuels and reduce damages caused by the use of fossil fuels, mainly CO_2.

This paper presents a review of geotechnical engineering for sustainable development, emphasizing climate change and energy depletion. Firstly, what sustainable development is and how it can be achieved via geotechnical engineering are discussed. Second, representative examples where geotechnical engineering contributes to sustainable development are identified. Finally, this paper introduces a novel rock excavation technique for underground space development, biotechnical convergence in geotechnical engineering and energy geotechnology as specific examples.

2. Geotechnical engineering for sustainable development

Development can be defined as human activities that benefit humanity by changing nature or society through current technologies and resources. Mankind has achieved civilization and economic growth at the expense of environmental destruction. Hence, sustainable development signifies development that harmonizes environmental conservation with continued human advancements (Fig. 1).

Climate change and energy depletion are the major problems that humanity faces in the current era. Artificial factors that contribute to recent climate changes are caused by the abuse of the earth's surface, which leads to the increase in greenhouse gas emissions. Mankind's use of fire, breeding of livestock, and agricultural activity have continuously changed the natural environment and caused destruction of large forest areas at a rapid pace since industrialization. Deforestation removes carbon sinks and adversely affects the reflectivity of the earth's surface, making it a major cause of climate change. In addition, a rapid increase in CO_2 emissions since the industrial revolution has led to the greenhouse effect and an increase in the global temperature. These artificial changes to the earth's climate have resulted in the rapid rise in global mean temperature, drastic reduction of glaciers in the polar regions, reduction of land area due to rises in sea level, desertification, etc. Active efforts and responses to climate change are required to maintain the status quo.

Fig. 1 Three components of sustainable development, modified from United Nations General Assembly (2005)

80% of the world's current energy consumption relies on fossil fuels such as oil, coal and natural gases (BP 2011). As shown in Fig. 2, the current recoverable reserves (recoverable years) of oil, natural gas, coal and uranium are 1.33 trillion barrels (45.7 years), 187.5 trillion m^3 (62.8 years), 826 billion tons (119 years) and 4.36 million tons

(70 years), respectively. These projections predicts the depletion of fossil fuel reserves within the next century. Compared to the limited energy reserves, the world's energy demand is projected to rise continuously due to population growth and increased standard of living. Under these circumstances, the world is facing an 'energy crisis' for its survival. The utilization of unconventional oil resources such as oilsand or shale gas can temporarily meet increased energy demands, but this temporal practice is insufficient to be an ultimate solution. Hence, a significant effort from every government is needed to secure stable supplies of oils and natural gas and to develop new energy sources that can replace conventional fossil fuels.

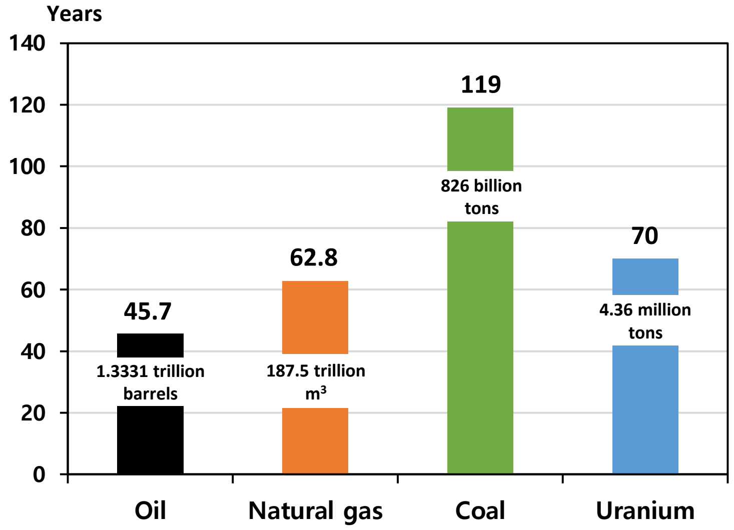


Fig. 2 Recoverable reserves and recoverable years of different resources (BP, 2010)

The role of geotechnical engineering is essential for sustainable development and in solving the problems of climate change and energy depletion. Among existing numerous examples of geotechnical engineering for sustainable development, some of the representative examples are presented in Fig. 3. The first example of geotechnical engineering for climate change mitigation is carbon capture and storage (CCS). CCS is the process of capturing CO_2 emissions and storing them permanently within the ground in order to reduce the amount of CO_2 in the atmosphere. The second example is the development of cement-less construction materials. Cement is a unique and indispensable construction material that is used worldwide for various purposes. However, cement production contributes to 5.3% of the world's total CO_2 emissions. The third example is anti-desertification. Intensified desertification is observed all around the world and its consequences casts a dark shadow over humanity's future. Over 6 million hectares (60 thousand km^2) of vast land is already desertified worldwide including the Saharan desert, which shows alarming expansion rates up to 10 km per year. Accelerated desertification results from low rainfall and soil erosion brought by climate change. The fourth example is disaster prevention and mitigation. Catastrophic natural disasters such as floods and landslides due to major earthquakes, tsunamis, typhoons and heavy rainfall continue to occur at an alarming rate in recent years. The fifth example is water retention and storage. A growing number of countries experience water shortages despite sufficient average annual precipitation. The increased pavement area due to urbanization prevents surface storage of rainfall. Thus, the collected rainwater flows directly into rivers and streams, worsening floods and droughts. The last example is the utilization of underground space for future cities. The earth's spatial domain can not only be expanded through skyscrapers, but also through the utilization of underground space. This allows the efficient 3 dimensional usage of space and lessens human susceptibility to the external environment.

The first example of geotechnical engineering provisions against energy depletion is the development of exploration technologies for energy resources. Advanced exploration technologies lead to enhanced detection of energy resources and more accurate reserve estimations. The second example is the development of ecofriendly renewable energy sources. The most universal form of renewable energy is hydropower, which is already nearing saturation levels worldwide whereas other forms of renewable energy sources such as geothermal power and wind power still have high growth potential. New technologies that can accurately design and assess the ground's geothermal properties need to be developed for optimal production of geothermal energy. Effective production of wind power requires appropriate design, construction and management of offshore foundations (e.g. suction piles), as most of the appropriate sites for harvesting wind power exist offshore. The third technology is the disposal of high level nuclear wastes. Nuclear power can be classified as a 'clean' energy source as it does not emit any greenhouse gases. However, various safety issues such as the disposal of used reactors and nuclear wastes needed to be assessed and a number of them can be resolved through developments in geotechnical engineering. The fourth technology is the restoration of energy infrastructures. Old energy infrastructures such as deteriorated power plants need to be improved to extend their lifespan and improve safety. The fifth technology is extreme engineering since a vast majority of useful resources is buried at extreme depths or in permafrost regions. The final technology is the effective recovery of unconventional oils and gases such as carbonate oils or methane hydrates. All of the aforementioned examples have strong ties with energy geotechnology.

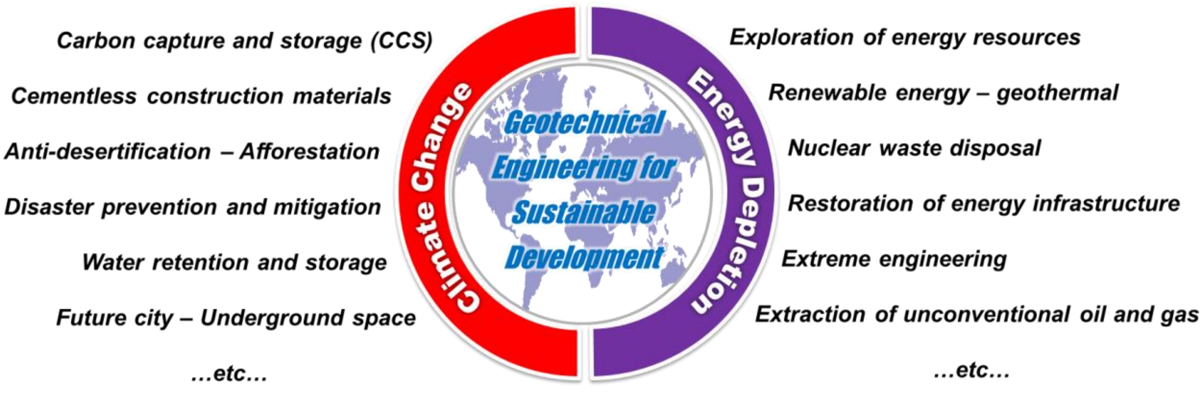


Fig. 3 Geotechnical engineering for sustainable development – Representative examples.

3. New rock excavation method for underground space development

The utilization of underground space for future cities expands the earth's spatial domain. This allows the 3 dimensional usage of space and lessens the susceptibility to the external environment. Rock excavation is necessary to generate underground facilities and tunnels. Hard rock excavation in urban areas is quite a challenge owing to unacceptable levels of excavation vibration and the necessity of rapid excavations. Blasting excavation method is used to break rock due to construction efficiency. However, explosions can induce serious levels of vibration and noise. The blasting vibration causes damage to nearby buildings in urban area excavation. In addition, the explosions weaken the ground stability and reliability due to the blasting impact and concentration. This weakening leads to poor fragmentation and high support costs (Arora and Dey, 2010).

Meanwhile, the use of a tunnel boring machine (TBM) is broadly utilized at present. However, the TBM method is not appropriate for mixed ground conditions or short tunnels and furthermore large underground space such as cavern.

The abrasive waterjet can remove target materials via the impact of abrasive particles accelerated by the high speed liquid flow (Zeng and Kim, 1996; Momber, 2004). Abrasive waterjet technology can help us solve these conventional excavation problems because it can achieve a higher accuracy and a lower vibration during rock excavation. In addition, abrasive waterjet technology has the advantages of not generating heat and mechanical stress, both of which can induce an excavation damage zone. Abrasive waterjets can be applied for rock cutting by themselves or for assisting mechanical excavation (Summers, 1995; Wang, 2003). Here, new abrasive waterjet-aided rock excavation methods are introduced.

3.1 Waterjet cutting combined with blasting method

An alternative tunnel excavation method combines the abrasive waterjet cutting technique and blasting process. In the overall excavation process, an abrasive waterjet initially performs continuous pre-cutting to generate a continuous free surface line along the perimeter of the tunnel face using a nozzle movement system. The deep pre-cutting is formed with multi-cutting performance until it reaches a certain cutting depth, which should be greater than the drill-hole depth for explosive charges. After completion of the pre-cutting process, holes are drilled to place the explosive charges, and then the blasting process is carried out. This method can minimize the blasting vibration level because the continuous pre-cutting free surface prevents the propagation of blasting elastic waves which are reflected at the free surface (Fig. 4).

To verify the effects of the proposed tunnelling method, field tests were performed. After blasting, overbreak and underbreak were measured for both abrasive waterjet-aided excavation method and smooth blasting method (Fig. 5). For the abrasive waterjet-aided excavation method, overbreak and underbreak (less than 3 cm) were rarely observed; on the other hand, overbreak and underbreak for smooth blasting method were found to be approximately 30 cm and 5 cm, respectively. The overbreak resulting from abrasive waterjet-aided excavation method was up to 90% less than that caused by the smooth blasting method.

In addition, the vibration velocity decreases with an increase in the distance from the explosive location due to material damping of the ground. In vibration comparison, the vibration velocities from the waterjet pre-cutting method are reduced to 40.1-55.0%, compared to the vibration velocity from the smooth blasting method.

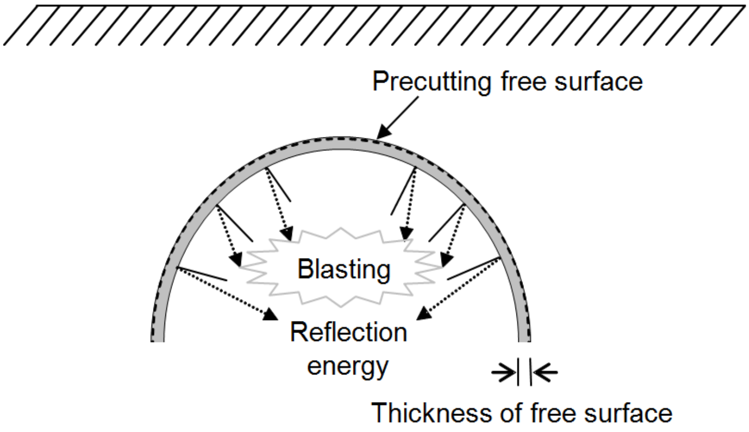


Fig. 4 Mechanism of blasting energy prevention using pre-cutting free surface (after Oh 2012)

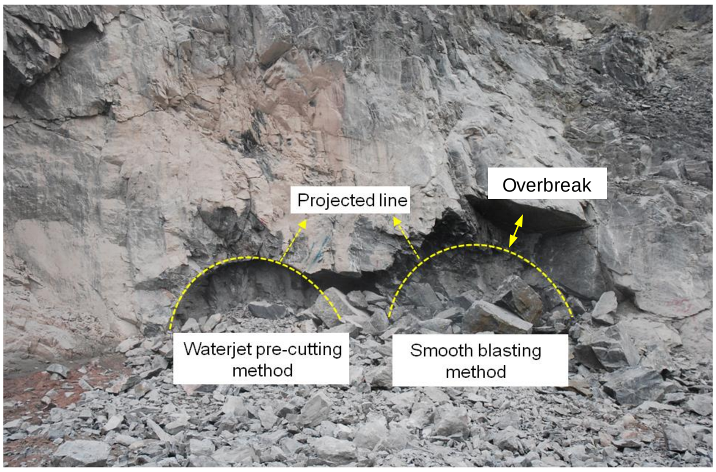


Fig. 5 Excavation results: abrasive waterjet aided rock excavation method (left) and smooth blasting method (right) (Oh et al. 2013)

3.2 Waterjet cutting combined with hydraulic hammer

A hydraulic hammer or a hydraulic impact hammer can excavate large areas of brittle material such as rock mass in mining or tunneling. Excavation by a common method by using hydraulic hammer is usually excavated from the center point to outer points on the tunnel’s bottom line. This method grows the size of the slotting hole by sequential and repetitive excavation procedures. However, the developed excavation method is totally the opposite of the above traditional method. First, the continuous free surface on the tunnel's perimeter was generated, and also generated several drilling holes using a drilling jumbo machine. As shown in Fig. 6, then, the rock breaking procedures were begun from the outer point to the center point and the step process of rock excavation using a hydraulic hammer between free surfaces was performed.

Two tests with the same site conditions were carried out; inside the tunnel and outside of the tunnel. Excavation volume of 60 m^3 was removed using developed method; it achieves high efficient excavation performance for hard rock (Fig. 7).

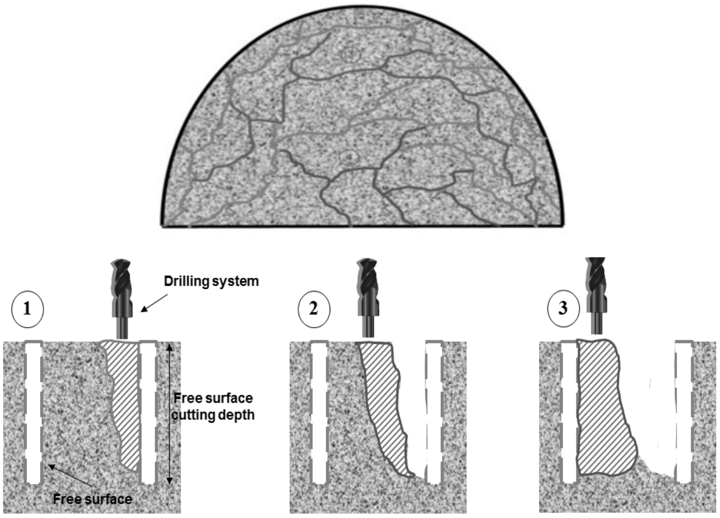


Fig. 6 Rock excavation with waterjet cutting free surface using hydraulic hammer

Fig. 7 Abrasive waterjet system combined with hydraulic hammer: (a) Free surface generation inside the tunnel, (b) Free surface generation on the tunnel's portal, (c) Breaking the rock mass inside the tunnel, (d) Breaking the rock mass on the tunnel's portal

3.3 Waterjet cutting combined with rock splitter

The hydraulic rock splitter excavates the target materials by induced high tensile strength, and the fracturing depth propagates through the major stress direction. The continuous free surface on the tunnel's perimeter was generated, and the drilling holes, between the free surfaces, were formed. Then, the feathers or cylinders were injected inside the drilling holes, which expanded with the induced hydraulic pressure. Finally, the rock mass between the free surfaces easily broke up into various sizes of fragments (Fig. 8).

The detailed construction process of the AWJ system combined with a rock splitter is divided into three main parts, cutting with the AWJ system, drilling with a jumbo drill machine, rock splitting with a rock splitter, and rock breaking with a hydraulic hammer, with a removable volume of 60 m^3.

Fig. 9 shows that a continuous fracturing depth between the slotting holes was generated when the rock splitting processes were performed. In this case, the slotting holes were drilled in a vertical direction and piston type cylinders were also injected inside the slotting holes. Therefore, fracturing depths mainly occurred and propagated in the vertical direction.

Furthermore, the cutting efficiency of the excavated areas was significantly different between the free surface and the tunnel's center point. When the excavation is proceeding through the tunnel's center point, the cutting efficiency is also proportionally decreasing. The average rock fragmentation size after the total construction process of the AWJ system combined with a hydraulic splitter was completed was 0.92 m by measuring six rock fragments or blocks.

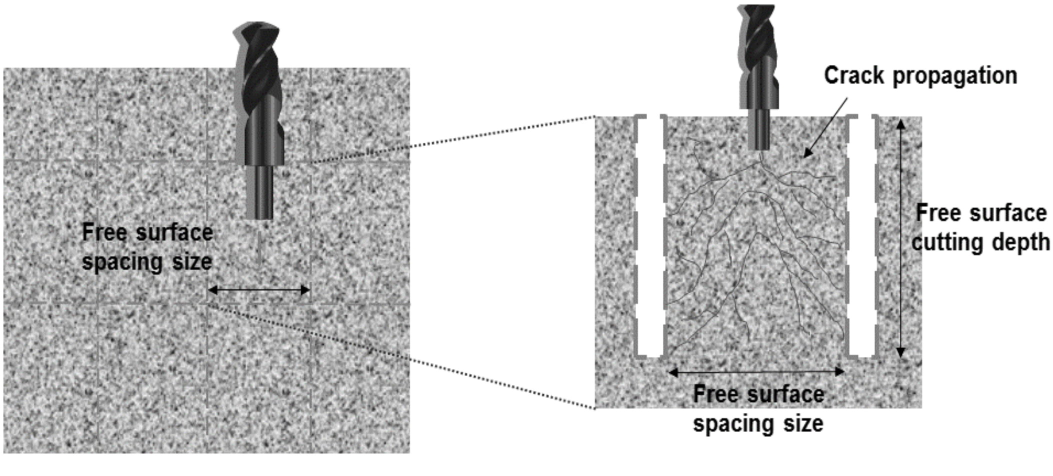


Fig. 8 Schematic process of rock excavation using a rock splitter between free surfaces

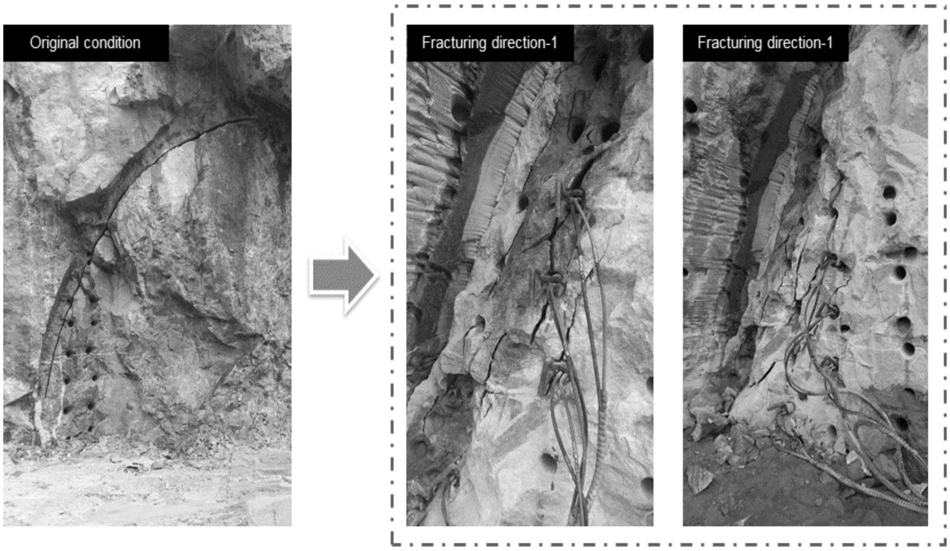


Fig. 9 Rock excavation using waterjet cutting combined with rock splitter

3.4 Summary

The alternative excavation methods with abrasive waterjet have various benefits: 1) the vibration level is significantly reduced by the generated free surface line; 2) excavation damaged zone is minimized during excavation; 3) overbreak and underbreak is minimized due to waterjet free surface; and 4) fragment size is reduced due to the efficient blasting effect, which can decrease overall construction cost. The excavation methods with a waterjet free surface can be applied to urban excavation construction with low vibration and high performance as well as to mega underground structure construction.

4. Biotechnical convergence in geotechnical engineering

The main purpose of soil treatment and improvement in geotechnical engineering is to modify the engineering properties of soil and ground such as strength (*i.e.*, resistance), hydraulic conductivity, and durability against repeating wetting and drying, as well as for environmental revitalization (Sherwood 1993). In geotechnical engineering practices, two typical approaches are commonly implemented: 1) mechanical improvement and 2) chemical treatment. Mechanical improvement is a process of reinforcing the strength of the soil through physical processes such as compaction, drainage, external loading (e.g., surcharge), consolidation, or other means. Chemical treatment involves chemical reactions such as hydration or pozzolanic reactions inside the soil to create artificial binding, such as the use of calcium silicate hydrate (C-S-H) between soil particles (Sherwood 1993).

As an alternative to such traditional soil treatment and improvement techniques, biological approaches are now being actively investigated in the field of geotechnical engineering, including microbe injection and byproduct precipitation. In particular, microbial induced polymers—or biopolymers—have been introduced as a new type of construction binder, especially for soil treatment and improvement.

4.1 Biogeotechnology with microbial biopolymers

Biopolymers are organic polymers that are synthesized by biological organisms. They consist of monomeric units that are bonded into larger formations. The use of biopolymers is, in fact, not an entirely new development in geotechnical engineering. Organic polymers such as natural bitumen, straw, and sticky rice have been used in ancient civilizations and can also be classified as biopolymers in a broad sense. In ancient Chinese civilization, sticky rice mortar was used as a binder. Sticky rice soup mixed with *Actinidia chinensis* cane juice, lime, loess, and river sand produced a mortar with good strength, high toughness, and water resistance (FuWei et al. 2009).

Biopolymers mixed with soil promote strengthening of the soil, including increased cohesion and strength, resistance to erosion, reduced permeability, *etc.*, by acting as a binder. The direct use of biopolymers in soil has several benefits over pre-existing biological soil treatment methods (Cole et al. 2012). The direct use of exo-cultivated biopolymers for soil treatment overcomes several shortcomings of other approaches (e.g., microbe injection) such as the need for microbial and nutrient injection, time for cultivation and excrement precipitation, and inappropriateness with clayey soils (De Muynck et al. 2010). Moreover, since biopolymers are readily found in nature and many are known to be harmless and edible, biopolymers can be considered eco-friendly substitutes for soil treatment. Several polysaccharide group biopolymers recently have been examined for use in geotechnical engineering.

A small quantity (*i.e.*, 0.5%–1% to the soil weight) of biopolymer in soil can produce significant strengthening effects (Fig. 10). In general, biopolymers have high specific surfaces with electrical charges, which enable direct interactions between the biopolymers and fine soil particles, thereby providing firm biopolymer-soil matrices with high strength (Chang et al. 2016).

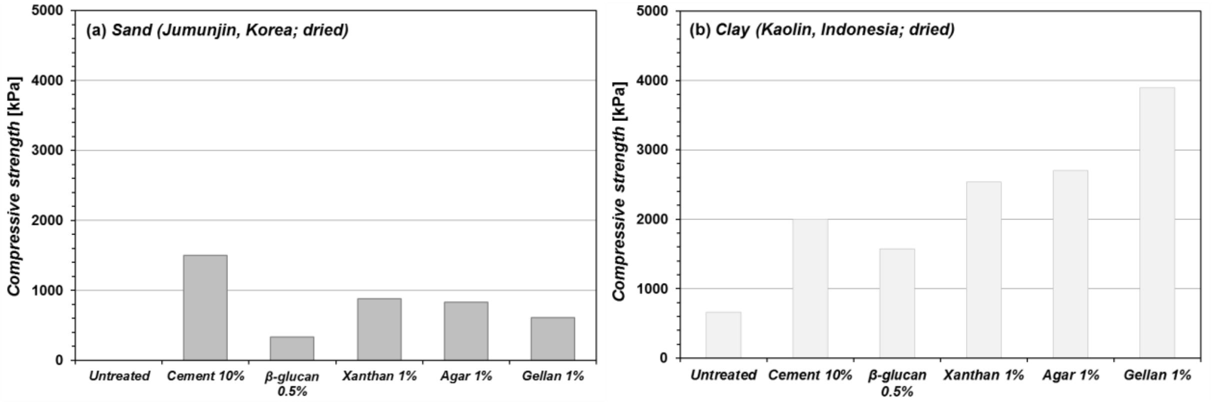


Fig. 10 Unconfined compressive strengths of (a) sand and (b) clay.

SEM images of sand-clay-biopolymer mixtures show that biopolymers directly bond with kaolinite particles, producing accumulated face-to-face clay layers, while sand surfaces remain clean or only film-type coats form around particles (Fig. 11). Thus, the strengthening is maximized in the presence of clayey particles due to the hydrogen and ionic bonding between the biopolymers and clay particles, which have electrical charges (Chang et al. 2015; Chang et al. 2015). However, the importance of biopolymer – clay interaction does not imply that sand particles have no role in the strengthening behavior, where well-graded soil with coarse particles treated with biopolymers shows higher strength than that obtained with pure clay, such as kaolinite (Chang et al. 2015).

In details, the inter-particle cohesion and friction angle behaviors of biopolymer (i.e., 1% gellan gum) treated soils show that shear strength characteristics of sandy soils (*i.e*., sand-clay mixtures) are more appropriate for practical applications than those of pure clay (Table 1). Thus, the strengthening mechanism of biopolymers in ordinary soils (*i.e.*, those containing both sand and clay) is believed to be a combination of the formation of biopolymer-clayey soil matrices (*i.e.*, cohesion enhancement) and friction improvement via coarse particles acting as aggregates.

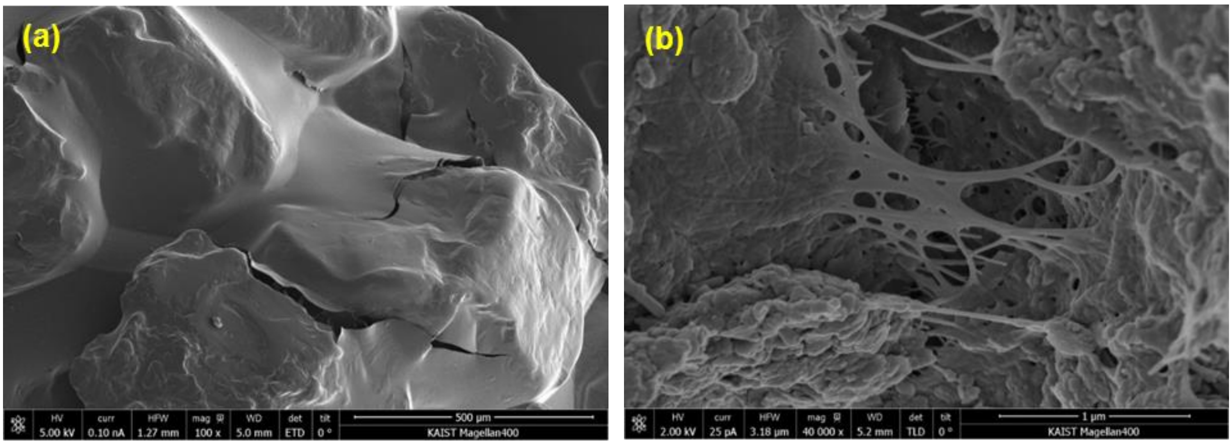


Fig. 11 SEM images of gellan gum biopolymer treated (a) sand and (b) clay.

Table 1 Inter-particle cohesion and friction angle values of 1% gellan gum biopolymer-treated soils obtained via direct shear tests.

Soil type	Pure sand	Sand:Clay = 8:2	Sand:Clay = 5:5	Pure clay
Cohesion [kPa]	11.8	14.0	30.4	22.4
Friction angle [°]	33.4	40.2	37.3	22.3

The elastic properties of biopolymer hydrogels, such as their tensile strength and stiffness, diminish exponentially with increased water content (Yakimets et al. 2007), resulting in a remarkable reduction in soil strength, to approximately 1/10th of the strength of the dried state in a fully saturated condition. However, the unconfined compressive strength of re-wetted biopolymer soil mixtures (*i.e.*, clayey soil ≥ 200 kPa; sandy soil ≥ 50 kPa) is much higher than that of untreated soils, and is immeasurable in most cases (Chang et al. 2015).

Furthermore, swelled viscous biopolymer hydrogels fill the pore spaces of soils (especially sand) and induce pore clogging, which reduces the hydraulic conductivity of soils by more than 3~4 orders of magnitude (Bouazza et al. 2009; Ivanov and Chu 2008; Khachatoorian et al. 2003). Biopolymers thus have potential to be applied for hydraulic purposes in geotechnical engineering, such as in slurry walls, (temporary) seepage barriers, and grouting (Chang et al. 2016).

4.2 Opportunities and future challenges for biopolymers in geotechnical engineering

Biopolymers can be introduced into the soil by various practical modes of application including mixing, injection, spraying, and grouting, and they can be used for building materials, earth pavement, and farmland erosion prevention (Fig. 12) (Chang et al. 2016). Furthermore, biopolymers form a stable gel matrix inside soil that does not damage the local ecosystem. Combined with their water retaining properties in soil, biopolymers are thought to be capable of promoting vegetation growth.

The largest advantage of direct biopolymer implementation compared to other bio-soil methods is that biopolymers can be produced ex-situ (*i.e.*, exo-cultivation) and applied in-situ with a higher degree of quality control, whereas MICP requires time-consuming in-situ cultivation. Moreover, biopolymers can be commercially mass produced, and react with soil particles immediately after mixing, which allows them to be utilized for temporary or rapid supporting purposes.

Meanwhile, application of biopolymers in soil engineering raises concerns about biodegradation with time. Moreover, biopolymers are highly sensitive to the presence of water, and therefore durability concerns involving wetting and drying cycles, as well as overall soil strength in the presence of water, must be addressed. However, a recent study shows consistent strengthening performance of xanthan gum biopolymer-treated soils up to two years after mixing (Chang et al. 2015). Thus, it is expected that the degradation characteristics of biopolymers would be acceptable when they are used for temporary or short-term practices. They would also be advantageous in certain applications because they would make further remediation processes or removal unnecessary, since the biopolymers are expected to naturally decompose with time.

Fig. 12 Possible biopolymer applications in geotechnical engineering practices.

To address other durability concerns, various types of biopolymers and/or practical implementation methods can be utilized together to improve the overall quality and reliability of biopolymer treated soils. Because most biopolymers exhibit high sensitivity to water, viable methods for increasing the effectiveness of biopolymer treated soils in water will greatly improve the reliability of these soils for ground improvement and stabilization. Several methods have been studied and conceived to resolve this issue, such as the use of biopolymers with thermo-gelation properties (Chang et al. 2015; Huang et al. 2007; Tang et al. 1997).

Another plausible solution is the use of protein based biopolymers. Protein based biopolymers, such as casein proteins, have been employed in a wide variety of fields such as in the manufacturing of adhesives. Since such proteins have lower hydrophilic properties than their polysaccharide biopolymer counterparts, soils that are stabilized by such proteins may provide higher resistance to water.

In addition to these methods, the use of cross-linking for biopolymers may provide a more powerful soil stabilizing method. Cross-linking is a technique used to greatly improve the properties of a specific material by introducing an agent that promotes interactions between separate polymer chains, thereby enhancing their overall strength. Cross-linking has also been used to enhance the properties of gel solutions. A double network hydrogel composed of two different biopolymers with a cross-linking agent was used to create a hydrogel with extremely high strength and durability (Gong et al. 2003; Nakayama et al. 2004).

Overall, a wide variety of methods can be applied to improve the mechanical properties of biopolymer treated soils, and as such, the use of biopolymers is emerging as a possible eco-friendly, sustainable method for soil improvement and stabilization. However, various further studies focusing on practical implementation methods and the development of suitable equipment are required to ensure desired construction performance and reliability of biopolymer applications for *in situ* geotechnical engineering purposes

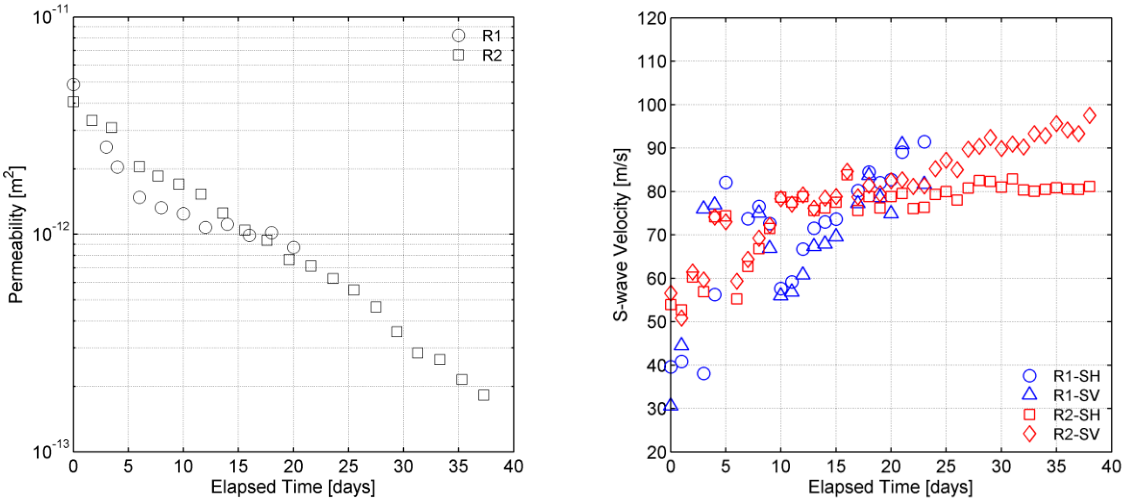
4.3 Seismic monitoring of microbial activities in subsurface

Microbial growth and activities are ubiquitous processes occurring in natural subsurface, and are known to have profound effects on the hydrological, mechanical, and chemical properties of geologic porous media [Mitchell and Santamarina, 2005]. Bacterial colonization and proliferation of biofilms on mineral surfaces are known to decrease permeability by several orders of magnitude and to cause bioclogging, which alters the hydraulic flow systems of porous media [Taylor and Jaffé, 1990]. Understanding and exploiting such ubiquitous bacterial activities has garnered significant interest in recent years because of the versatility of these treatments in geo-engineering applications, such as soil improvement, hydraulic barrier installation, and microbial enhanced oil recovery (MEOR) [DeJong et al., 2014; Ivanov and Chu, 2008; Morales et al., 2010]. For instance, bio-mineralization processes such as microbial induced calcite precipitation (MICP) have been proposed as a promising method for improving soil stiffness and strength [e.g., DeJong et al., 2006 and 2014; van Paassen et al., 2010; Whiffin et al., 2007] and for preventing CO2 leakage from geologic storage sites by reducing the porosity of the leakage pathways [e.g., Phillips et al., 2012]. The production of nitrogen (N2) gas in water-saturated sediments by denitrification can improve the dynamic undrained strength and liquefaction resistance of a medium [DeJong et al., 2014; Rebata-Landa and Santamarina, 2012]. The use of biopolymers such as β-1,3/1,6-glucan as cementing agents for soil improvement has also been reported to have a profound effect on mechanical properties, such as an increase in compressive strength [Chang and Cho, 2012].

Bacterial activities and their products, such as biosurfactants, solvents, miscible gases, and acids, can also mobilize oil trapped in reservoirs and improve oil recovery via various mechanisms [Youssef et al., 2009]. In particular, the selective plugging of high permeability zones, caused by the accumulation of insoluble biopolymers produced by bacteria in pores, has been considered as an efficient method for enhancing the sweep efficiency of water flow for microbial enhanced oil recovery (MEOR), a process sometimes referred to as microbial profile control [Cusack et al., 1992; Gray et al., 2008; Jenneman et al., 2000; Lappan and Fogler, 1996].

Successful microbial bioclogging treatments require appropriate monitoring techniques; geophysical monitoring techniques are attractive because they can provide spatial and temporal information on bacterial growth and activities in the subsurface. Such monitoring datasets can be used to evaluate the status of plugged reservoir sections and optimize re-treatment if the plug degrades. Only a few biogeophysical studies have attempted to monitor bacterial clogging in porous media by using either seismic techniques [e.g., Davis et al., 2009 and 2010; Jaiswal et al., 2014; Kwon and Ajo-Franklin, 2013] or geo-electrical and nuclear magnetic resonance (NMR) techniques [e.g., Abdel Aal et al., 2004; Atekwana and Slater, 2009; Codd et al., 2011; Kirkland et al., 2015; Wu et al., 2014]. To date, the primary finding from previous studies [e.g., Davis et al., 2009; and 2010; Jaiswal et al., 2014; Kwon and Ajo-Franklin, 2013] is that the formation of a soft biopolymer or biofilm in porous media increases P-wave attenuation (1/QP) at an ultrasonic frequency range (~several hundreds kHz). However, the impact of soft biopolymer production on S-wave propagation or P-wave propagation at a lower frequency range remains poorly understood.

Kwon and Ajo-Franklin (2013) and Noh et al. (2016) investigated the feasibility of using both P- and S-wave responses (velocity and attenuation) of porous media for monitoring in situ accumulation of a bacterial biopolymer in sediments. Column experiments with fine sands, where the model bacteria Leuconostoc mesenteroides were stimulated to produce insoluble biopolymer, were conducted while monitoring changes in permeability and P- and S-wave responses. The bacterial biopolymer reduced the permeability by more than one order of magnitude, occupying ~10% pore volume after 38 days of growth (Fig. 13a). This substantial reduction was attributed to the bacterial biopolymer with complex internal structures accumulated at pore throats. S-wave velocity (VS) increased by more than ~50% during biopolymer accumulation (Fig. 13b); this indicated that the bacterial biopolymer caused a certain level of stiffening effect on shear modulus of the unconsolidated sediment matrix at low confining stress conditions. Whereas replacing pore water by insoluble biopolymer was observed to cause minimal changes in P-wave velocity (VP) due to the low elastic moduli of insoluble biopolymer. The spectral ratio analyses revealed that the biopolymer formation caused a ~50–80% increase in P-wave attenuation (1/QP) at the both ultrasonic and sub-ultrasonic frequency ranges, at hundreds of kHz and tens of kHz, respectively, and a ~50–60% increase in S-wave attenuation (1/QS) in the frequency band of several kHz. Their results suggest that in situ biopolymer formation and the resulting permeability reduction can be effectively monitored by using P- and S-wave attenuation in the ultrasonic and sub-ultrasonic frequency ranges. This suggests that field monitoring using seismic logging techniques, including time-lapse dipole sonic logging, may be possible.



(a) (b)

Fig. 13 Changes in (a) permeability and (b) S-wave velocity caused by bacterial biopolymer formation (Kwon and Ajo-Franklin, 2013).

4.4 Summary

Recent studies have shown that biopolymers can strengthen soils, and they offer several advantages in such applications, including being environment-friendly and effective at low concentrations. Several studies have shown that the strengthening induced by biopolymer treatment is maximized in the presence of fines, especially clay particles. For polysaccharide-type biopolymers, hydroxyl groups on the polymer surfaces induce hydrogen bonding with water molecules, making them hydrophilic, and enabling the formation of firm (*i.e.*, viscous) hydrocolloids or hydrogels.

Meanwhile, when water is scarce, as in conditions of drought or dry soils, biopolymers can form direct hydrogen bonds with clay particles, or indirect ionic bonds with these particles, in the presence of intermediate ions such as alkali- or alkali earth-metal ions in the soil. Direct and indirect bonding leads to the formation of a firm biopolymer-clay matrix, which provides a significant increase in soil cohesion. Proper mixing of coarse particles, clay particles, and biopolymers is thus expected to provide optimal strengthening effects, due to the combination of increased mechanical friction between coarse particles, and a cementation effect between biopolymer-clay matrices.

5. Energy Geotechnology

Geotechnical engineering has been applied in various field of energy technology for sustainable development, for example, in geologic carbon dioxide (CO_2) sequestration (GCS) as a part of the CO_2 Capture and Storage (CCS), unconventional energy recovery such as methane hydrate, shale gas, oil sand, etc.

5.1 Methane recovery from gas hydrate-bearing sediments

Methane hydrate is an ice-like solid compound in which methane molecules are locked within lattice structures of water. Hydrate-bearing sediment, which is found in offshore and permafrost regions, are anticipated to exist in 113 regions according to geophysical, geochemical, and geological investigations (Kvenvolden and Lorenson, 2010). During 30 years, research has shown that the global estimation of methane gas in the hydrate-bearing sediments ranges from (1-5)x10^{15} m^3 STP (Milkov, 2004), which is much bigger than all of fossil fuels. Currently fourteen main projects are underway around the world (Boswell and Collett, 2010). However, there are many geotechnical problems which should be solved before the production of methane in situ (Fig. 14).

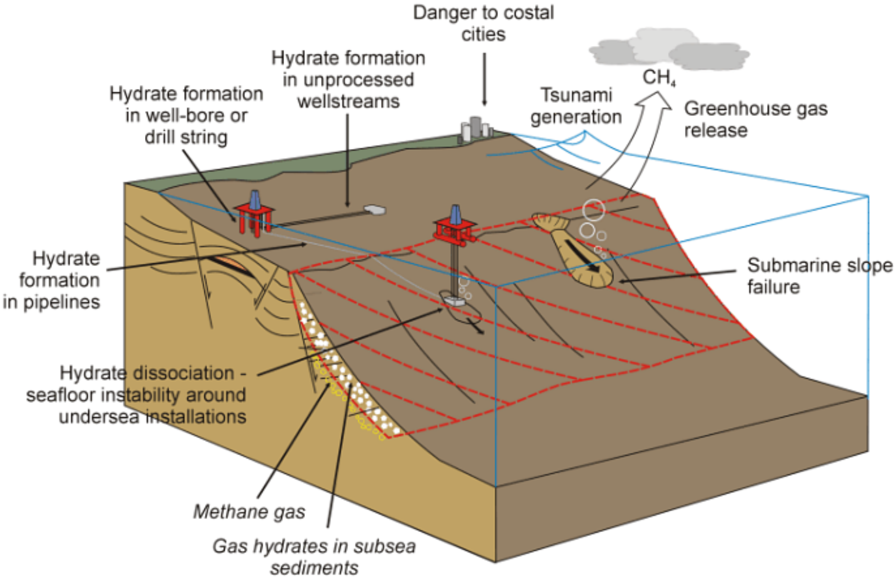
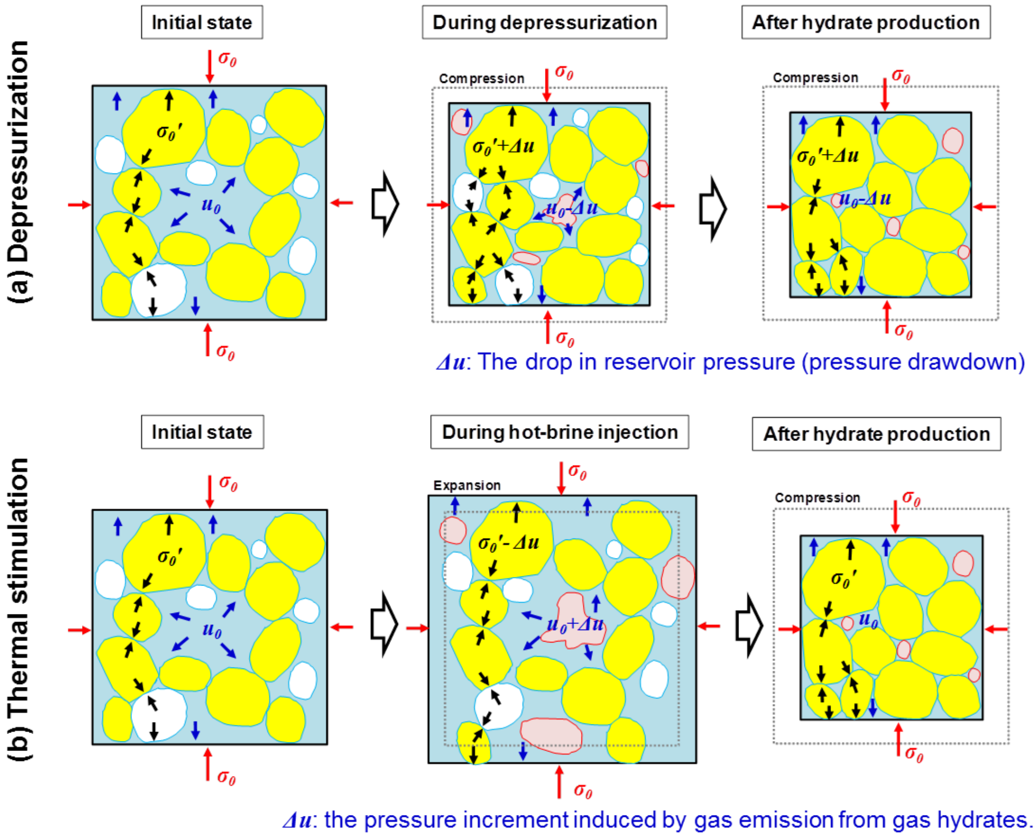


Fig. 14 Geotechnical problems related to the production of methane in situ (image from www.pet.hw.ac.uk).

There are three main production methods of gas recovery from methane hydrate layers: (1) depressurization, in which the methane hydrate is dissociated by lowering the well pressure (Fig. 15a); (2) thermal stimulation, in which the hydrate is dissociated by injecting hot fluid into the production well (Fig. 15b); and (3) chemical stimulation, in which the hydrate is destabilized by injecting inhibitors and their combinations (Moridis, 2003; Makogon, 1997; Holder et al., 1984; Pawar et al., 2005). For successful methane recovery from hydrate deposits, depressurization is considered the most productive and effective method (Moridis and Reagan, 2007; Collett, 2007).



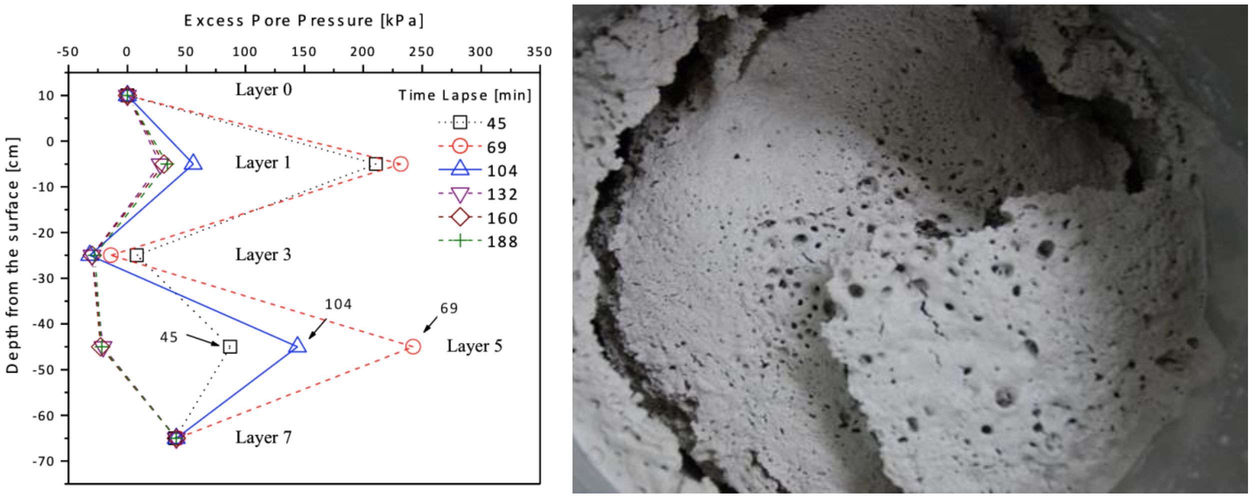
Δu: The drop in reservoir pressure (pressure drawdown)

Δu: the pressure increment induced by gas emission from gas hydrates.

Fig. 15 Geotechnical aspect of gas hydrate production

The thermal stimulation of hydrate-bearing sediments is associated with excess pore pressure generation, plastic deformation of sediments, and seafloor deformation. While these emergent phenomena are expected to occur as a coupled process during unexpected or intentional hydrate dissociation, reliable assessments of the geo-hazards associated with such hydrate dissociation, such as sediment instability and borehole failure, is important. For example, drilling and operating a wellbore through hydrate deposits presents a significant challenge because of insufficient knowledge of the geomechanical responses of sediments undergoing hydrate dissociation. Kwon et al. (2010 and 2013) investigated the geomechanical and thermal responses of hydrate-bearing sediments subjected to thermal stimulation via a numerical modeling approach and a physical modeling approach using a large pressure vessel and geotechnical centrifuge equipment, respectively.

Gas hydrate dissociation produces a pronounced volume expansion, owing to the release of a large amount of gas (Kwon et al. 2008; Holtzman and Juanes 2011). Specifically, if hydrate dissociates in clayey sediments with a permeability of ~1 mD, the released gas cannot escape, and hence the pore fluid pressure in sediments can increase by several megapascals, or fractures in the medium can be generated when the gas pressure exceeds the effective stress of the skeleton (Kwon et al. 2010; Holtzman and Juanes 2011). However, if hydrate dissociation occurs in sandy sediments with a permeability larger than 1 D, it has been demonstrated that there is only a slight development of excess pore fluid pressure because the over-pressure dissipates rapidly to the surrounding regions (Kwon et al., 2010). Thus, when thermally stimulating hydrate-bearing sediments, the magnitude of the excess pore pressure generation is governed by the relative rate of the pressure diffusion to the hydrate dissociation, as presented in Kwon et al. (2010). Whereas, in spite of the high permeability of the tested sediments in Kwon et al. (2013), ~240 kPa of excess pore pressure was caused by hydrate dissociation near the heat source, owing to continued hydrate dissociation during pressure diffusion, implying a possible volume expansion at the hydrate dissociation region (Fig. 16a). Such excess pore pressure in the order of several hundreds of kilopascal, whether it is caused by hydrate dissociation or by fluid migration from far fields, will lead to either sediment volume expansion, uplifting deformation at the seafloor, or fracture generation in sediments (see Fig. 16b).



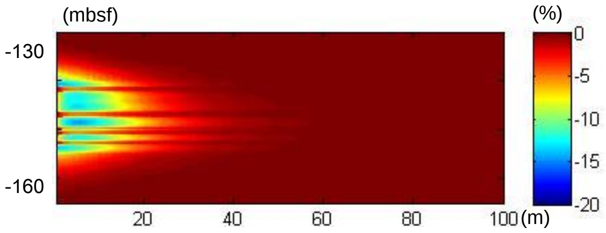
(a)

(b)

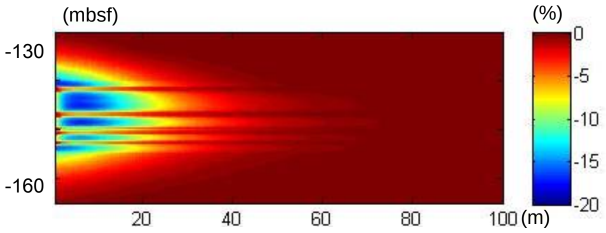
Fig. 16 (a) Change in excess pore pressure and (b) observed fractures and gas seep on the soil surface after thermal dissociation of hydrates.

The dissociation of gas hydrate in sediments relieves the cementation (i.e., decementation) and decreases the stiffness. Moreover, as solid hydrate crystals vanish, the soil stiffness further decreases. This implies possible post-dissociation subsidence where the sediments in the hydrate dissociation region will eventually undergo downward deformation (settlement) by weight of overlying sediments owing to the reduced stiffness (or increased compressibility). In Kwon et al. (2013), thermal dissociation of hydrate caused at a maximum ~25% decrease in V_S, or an ~40% decrease in the shear stiffness of sediments, when the initial S_h was ~32–39%, because of the vanishing of solid hydrate crystals that were cementing the mineral grains or bearing load. This implies the potential of post-dissociation subsidence at the seafloor, of the order of several meters, during gas production from hydrate-bearing deposits. In addition to this, such post-dissociation subsidence may apply a downward force to well structures, but lateral skeletal stress in a yielded zone is significantly reduced because of plastic deformation. As a result of post-dissociation subsidence and lack of lateral stress, a slender well structure could be damaged, particularly at a region where a large volume expansion occurs and a yield zone is developed.

The depressurization method, however, induces significant geomechanical behaviors such as large volume contraction, settlement, consolidation in the surrounding hydrate-bearing sediment (Fig. 17). This is because the difference between well and surrounding pore pressure results in effective stress, and because stress relaxation occurs due to hydrate dissociation. Moreover, these kinds of geomechanical responses can be aggravated by sand production problems if the formation type of the target site includes sediments consisting of sand and fractured mud. Hence, the stability of the production equipment (i.e., production wellbore, monitoring equipment) can be affected due to the destabilized sediments in the depressurized and hydrate-dissociated region. Moreover, gas productivity can be reduced due to reduction of permeability in the large region consolidated by depressurization. Therefore, it is strongly recommended that the stability and productivity of methane recovery by the depressurization method be carefully evaluated. This can only be achieved by thermal-hydraulic-mechanical (THM)-coupled numerical modeling and simulations (Moridis et al. 2013).



(a) after 7 days



(b) after 14 days

Fig. 17 The spatial distribution of the volumetric strain around the production well head during a methane production test – Numerical modeling results.

5.2 Geologic CO_2 sequestration (GCS) into shallow marine sediments

Since the Industrial Revolution, CO_2 emission rates have increased dramatically due to the increased use of fossil fuels. Several CO_2 emission mitigation technologies have been proposed to stabilize the atmospheric CO_2 concentrations, including the recycling of materials and the use of renewable energy, nuclear fusion, and biofuels. Among these, carbon capture and storage (CCS) strategies represent a major alternative for reducing atmospheric CO_2 concentrations in a relatively short time at a low cost compared to other technologies (IPCC, 2005; Espinoza et al., 2011; Pires et al., 2011). Currently, several large-scale CCS projects are in planning or operational stages around the world.

The long-term storage of CO_2 in deep geological formations, known as geological CO_2 storage (GCS), has the potential to reduce CO_2 emissions by 20%, which is considered to be the amount necessary to stabilize atmospheric CO_2 levels over the next century (Haszeldine, 2009). For these reasons, GCS technology has been developed by several leading countries. However, existing GCS methods worldwide require a particular geological structure consisted of highly pervious rock formation (e.g., sandstone layer) imbedded in impermeable layers (i.e., cap-rocks). In accordance with this geological requirement, there are still unsolved difficulties in GCS technology such as the shortage of proper sites, challenges in the long-range CO_2 transportation, deep drilling and injection and restricted storage capacity, which substantially increase the cost of using GCS methods.

CO_2 can be stored in unconsolidated sediments under CO_2 hydrate-bearing sediments (Fig. 18). CO_2 hydrates are formed in seabed under low temperatures and high pressures (Brewer et al., 1999; Inagaki et al., 2006). Previous studies on natural gas hydrate-bearing sediments (e.g. Nimblett and Ruppel, 2003) and preliminary studies on CO_2 hydrate-bearing sediments (e.g. Koide et al., 1995; Tohidi et al., 2010) show that the permeability of the sediments is significantly reduced by the formation of gas hydrates, in which becomes a self-trapping mechanism. Furthermore, the self-preservation response of CO_2 hydrates slows the CO_2 hydrate dissociation process (Kwon et al., 2008), which serves to mend unintended fractures of CO_2 hydrate-bearing sediments, thereby severely diminishing the transport of CO_2 fluids (Stern et al., 2001; Kuhs et al., 2004). Thus, it has been suggested that CO_2 hydrates can be used as primary or secondary safety factors of CO_2 geological storage in marine unconsolidated sediments (Koide et al., 1997; House et al., 2006; Rochelle et al., 2009). Furthermore, unconsolidated sand sediments have advantages over consolidated rocks (e.g., sandstones) in that the CO_2 storage capacity of the former is higher than that of the latter due to the high porosity of unconsolidated sandy sediments (40–60%). In addition, the CO_2 injectability of unconsolidated sand sediments is superior because of their high permeability (0.1–10 darcys) resulting from wide and well-connected pore spaces.

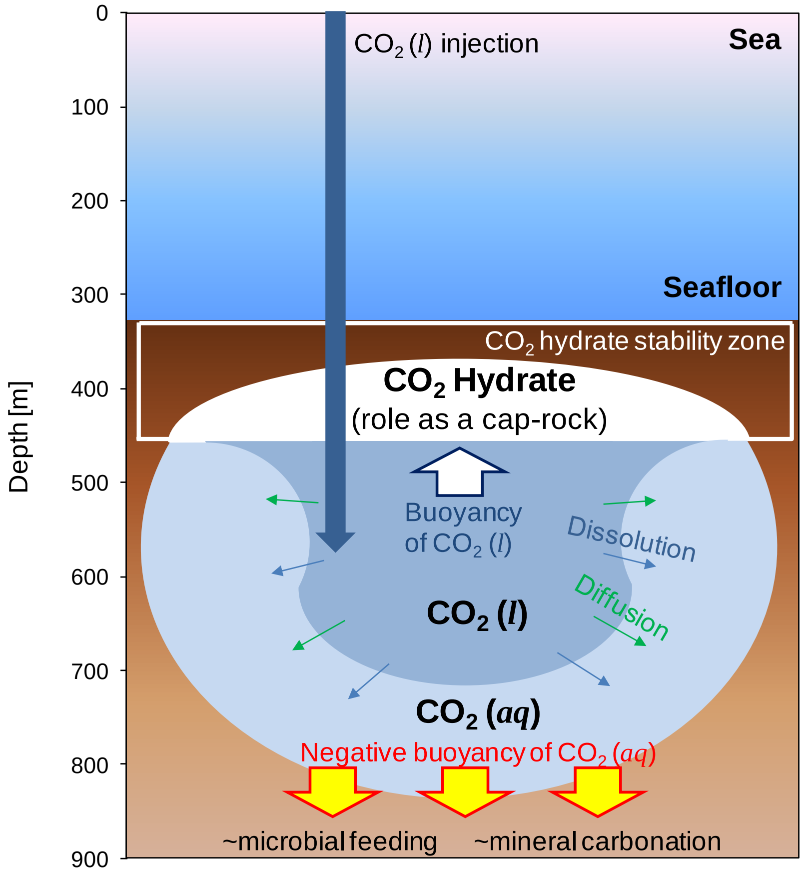


Fig. 18 Permanent CO_2 sequestration in shallow marine sediments using self-trapping mechanism of CO2 hydrate (after House et al., 2006)

Geologic CO_2 storage (GCS) involves (1) the selection of a suitable site with an adequate geologic structure, (2) the injection of CO_2, (3) the storage of CO_2 by physical or geochemical trapping mechanisms, and (4) the monitoring of the stored CO_2 to detect any unwanted leakage. Not only proper technologies should be developed and chosen for each process, but also geological characteristics and complex behavior of CO_2 and CO_2 hydrate-containing sediment should be evaluate and considered in GCS technology.

For successful applications of CO_2 hydrate formation in CO_2-injected deposits, detection and monitoring of the regions undergoing those processes are critical (Kim et al., 2014). Techniques based on seismic waves (e.g., seismic survey methods and sonic logging) appear to be one of the most appropriate viable options for monitoring these processes in sediments. Seismic wave velocities are can also analogous to be converted to soil small-strain stiffness (Clayton et al., 2005) and used as essential input parameters for numerical simulations of CH_4 hydrate production and CO_2 sequestration using CO_2 hydrate.

However, little effort has yet been made to measure seismic velocities of gas hydrate-bearing fine-grained sediments in a low-to-medium hydrate saturation regime.

Moreover, the cementation effect of hydrate formation on the seismic velocities and mechanical stiffness of fine-grained sediments remains poorly understood. This knowledge gap is hampering the reliable estimation of gas hydrate saturation in such sediments and the calibration of logging and seismic exploration results acquired in hydrate occurrence regions. Considering the complex nature of the hydrate formation process in fine-grained sediments, a key challenge appears to be the design of well-controlled laboratory experiments that can control hydrate quantity, achieve excess water conditions and monitor seismic responses.

The migration of injected CO_2 should be monitored to detect the leakage of stored CO_2. In addition, the CO_2 saturation of the sediments in close proximity to the CO_2 injection sites should be monitored to estimate the future storage capacity and long-term fate of the CO_2. The P-wave monitoring method has been widely used for existing geological CO_2 storage (e.g., Arts et al., 2004; White, 2009). CO_2 saturation is a major factor affecting the P-wave velocity of unconsolidated sediments containing CO_2 because the P-wave velocity of CO_2 is slower than that of seawater. The physical properties of CO_2, such as P-wave velocity, bulk modulus, and density, vary with thermodynamic conditions such as temperature and pressure, whereas the temperature and pressure of unconsolidated sediments change with depth due to the geothermal and hydrostatic pressure gradients of the storage site. Thus, changes in the physical properties of CO_2 should be considered for P-wave monitoring during its buoyant upward migration. For example, Kim et al. (2015) suggested P-wave velocity model of unconsolidated sediments containing CO2 and verified the model with experimental data as shown in Fig. 19. Thus, the developed model can be readily applied to general numerical analyses and seismic exploration.

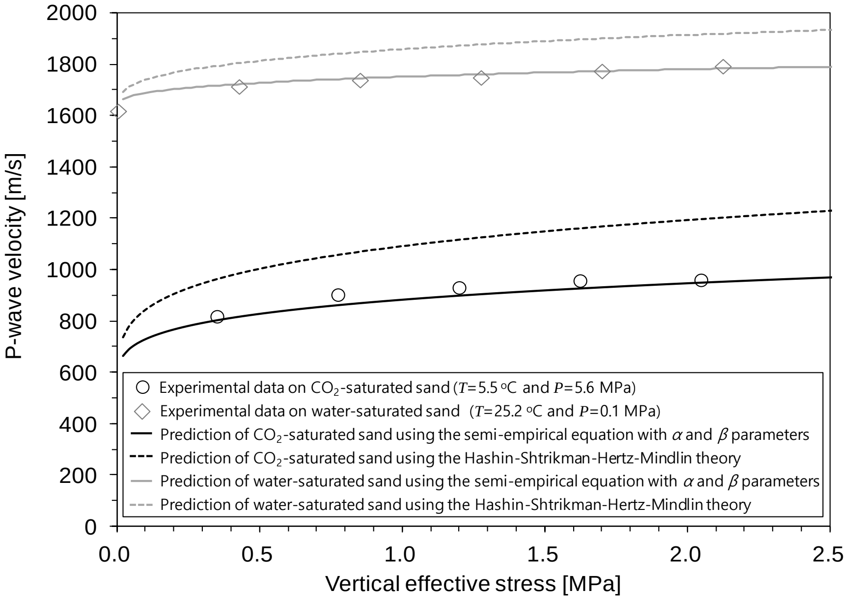


Fig. 19 P-wave velocity of CO_2-saturated unconsolidated sediment specimen versus effective stress (Kim et al., 2015). Hollow points represent experimental data on the

CO_2-saturated unconsolidated sand specimen at a temperature of 5.5 °C and pressure of 5.6 MPa. Hollow diamonds represent experimental data for the water-saturated unconsolidated sand specimen. The black and gray solid lines represent the predicted P-wave velocity of the CO_2-saturated and water-saturated specimens. The black and grey dashed lines represent the predicted P-wave velocity of CO_2-saturated and water-saturated specimens by using the Hashin–Shtrikman–Hertz–Mindlin theory, respectively.

5.3 Energy geotechnology

A summary of all energy resources including fossil fuels (petroleum gas and coal), and nuclear and renewable sources (wind, solar, hydroelectric, geothermal, biofuels, and tidal energy), along with a brief listing of associated geotechnical engineering involvement is given in Table 2. Energy Geotechnology is a new frontier for the geotechnical engineering field, with unprecedented relevance to a critical worldwide challenge. Indeed, energy geotechnology is an integral part of the development of a sustainable energy strategy.

The technical questions are fascinating and require multi-scale analyses, consideration of large-spatial and long-time scales, and the detailed assessment of hydro-chemo-thermo-bio-mechanical coupled processes. The next generation of engineers will require the proper education to address the needs in Energy Geotechnology.

Table 2 Summary of energy geotechnology (Santamarina and Cho, 2011)

FOSSIL FUELS (C-BASED)			**RENEWABLE**		**NUCLEAR**
Petroleum	Gas	Coal	Wind	Geothermal	
fines and clogging; sand production; borehole instability; heavy oil and tar sand; carbonate oil; EOR	Methane hydrates; reservoir stability; shale gas; hydraulic fracturing; optimal extraction; low-T LNG storage;	Characterization; subsurface response; mine excavation and instability; gas recovery	Off/onshore foundations; characterization; periodic loading	Drilling, fracture formation; heat transfer; energy piles; optimization	Engineered soils; decommission; leak detect and repair; long-term behavior and monitoring
Geological Storage					
CO_2 sequestration			*Energy storage*		*Waste storage*
Geoenvironmental Remediation					
Efficiency and Conservation Energy efficient construction technology; Embodied energy in infrastructure projects					

Note: Hydroelectric: global capacity almost saturated; Biofuels: water, land use, energy efficiency, and food impact; Tidal: at selected locations only

6. Conclusions

All forms of development impose an inevitable burden on the natural environment. For sustainable development, this burden must be within the self-resilient limit of the natural environment. This is because nature conservation and environmental protection, a major keystone in the concept of sustainable development, need to compete with powerful opponents such as technological convenience and economic validity in the real world. Thus, sustainable development implies to engineers in numerous fields a difficult goal in simultaneously achieving all of them. Since geotechnical engineering deals with the earth, it can make a great contribution to sustainable development in an efficient way.

Best examples are the development of underground space for new generation and culture and the development of energy with minimum impact on the natural environment. The boundaries of human life are limited to the physical space on earth and are inevitably based on the ground. Hence, the utilization of underground space has the potential of doubling the available space for human use. In addition, the use of conventional fossil fuels are limited by various technological and economic restrictions, whereas the ground is an area of opportunity that can both supply conventional and non-conventional fossil fuels and reduce damages caused by the use of fossil fuels, mainly CO_2.

Energy geotechnology is a new frontier for the geotechnical engineering field, with unprecedented relevance to a critical worldwide challenge. Indeed, energy geotechnology is an integral part of the development of a sustainable energy strategy. The technical questions are fascinating and require multi-scale analyses, consideration of large-spatial and long-time scales, and the detailed assessment of hydro-chemo-thermo-bio-mechanical coupled processes. The next generation of engineers will require the proper education to address the needs in energy geotechnology.

Acknowledgements

This research was supported by the basic research project of the Korea Institute of Geoscience and Mineral Resources (KIGAM) funded by the Ministry of Knowledge Economy of Korea and a grant (16AWMP-B114119-01) from Water management research Program funded by Ministry of Land, Infrastructure and Transport of Korean government. The author is very thankful to Prof. Tae-Hyuk Kwon, Dr. Ilhan Chang, Dr. Tae-Min Oh, Dr. A-Ram Kim, and Mr. Jiwon Kim for their valuable information and comments.

References

Arora, S. and Dey, K. (2010), “Estimation of near-field peak particle velocity: a mathematical model”, *J. Geol. Min. Res.*, **2**(4), 68-73.

Arts, R., Eiken, O., Chadwick, A., Zweigel, P., Van der Meer, L. and Zinszner, B. (2004), “Monitoring of CO_2 injected at Sleipner using time-lapse seismic data” *Energy*, **29**(9), 1383-1392.

Abdel Aal, G.Z., Atekwana, E.A., Slater, L.D. and Atekwana, E.A. (2004), “Effects of microbial processes on electrolytic and interfacial electrical properties of unconsolidated sediments”, *Geophys. Res. Lett.*, **31**(12), L12505-1.

Atekwana, E.A. and Slater, L.D. (2009), “Biogeophysics: A new frontier in earth science research”, *Rev. Geophys.*, **47**(4), RG4004.

Boswell, R. and Collett, T. S. (2011), “Current perspectives on gas hydrate resources” *Energ. Environ. Sci.*, **4**(4), 1206-1215.

Bouazza, A., Gates, W.P. and Ranhith, P.G. (2009), “Hydraulic conductivity of biopolymer-treated silty sand”, *Geotechnique*, **59**(1), 71-72.

BP (2011), Energy Outlook 2030.

BP (2010), Statistical review of world energy 2010.

Brewer, P.G., Friederich, G., Peltzer, E.T. and Orr, F.M. (1999), “Direct experiments on the ocean disposal of fossil fuel CO_2”, *Science*, **284**(5416), 943-945.

Chang, I. and Cho, G.C. (2012), “Strengthening of korean residual soil with β-1, 3/1, 6-glucan biopolymer”, *Constr. Build. Mater.*, **30**, 30-35.

Chang, I., Im, J., Prasidhi, A.K. and Cho, G.C. (2015), “Effects of Xanthan gum biopolymer on soil strengthening”, *Constr. Build. Mater.*, **74**, 65-72.

Chang, I., Prasidhi, A. K., Im, J. and Cho, G.C. (2015), “Soil strengthening using thermo-gelation biopolymers”, *Constr. Build. Mater.*, **77**, 430-438.

Chang, I., Im, J. and Cho, G.C. (2016), “Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering”, *Sustainability*, **8**(3), 251.

Clayton, C.R.I., Priest, J.A. and Best, A.I. (2005), “The effects of disseminated methane hydrate on the dynamic stiffness and damping of a sand”, *Geotechnique*, **55**(6), 423-434.

Codd, S.L., Vogt, S.J., Hornemann, J.A., Phillips, A.J., Maneval, J.E., Romanenko, K.R., Hansen, L., Cunningham, A.B. and Seymour, J.D. (2011), “NMR relaxation measurements of biofouling in model and geological porous media”, *Org. Geochem.*, **42**(8), 965-971.

Cole, D., Ringelberg, D. and Reynolds, C. (2012), “Small-Scale Mechanical Properties of Biopolymers”, *J. Geotech. Geoenviron.*, **138**(9), 1063-1074.

Collett, T. (2007), “Arctic Gas Hydrate Energy Assessment Studies”, *The Arctic Energy Summit*, Anchorage, Alaska, USA, 15-18.

Cusack, F., Singh, S., Mccarthy, C., Grieco, J., Rocco, D.M., Nguyen, D., Lappin-Scott, H. and Costerton, J.W. (1992), “Enhanced oil recovery-three-dimensional sandpack simulation of ultramicrobacteria resuscitation in reservoir formation”, *J. Gen. Microbiol.*, **138**(3), 647-655.

Davis, C.A., Pyrak-Nolte, L.J., Atekwana, E.A., Werkema, D.D. and Haugen, M.E. (2009), “Microbial-induced heterogeneity in the acoustic properties of porous media”, *Geophys. Res. Lett.*, **36**(21), L21405.

Davis, C.A., Pyrak-Nolte, L.J., Atekwana, E.A., Werkema, D.D. and Haugen, M.E. (2010), “Acoustic and electrical property changes due to microbial growth and biofilm formation in porous media”, *J J. Geophys. Res. Biogeosci.*, **115**(G3), G00G06.

DeJong, J.T., Fritzges, M.B. and Nüsslein, K. (2006), “Microbially induced cementation to control sand response to undrained shear”, *J. Geotech. Geoenviron.*, **132**(11), 1381-1392.

DeJong, J., Proto, C., Kuo, M. and Gomez, M. (2014), “Bacteria, biofilms, and invertebrates: The next generation of geotechnical Engineers?”, *Geo-Congress 2014 Technical Papers*, 3959-3968.

De Muynck, W., De Belie, N. and Verstraete, W. (2010), “Microbial carbonate precipitation in construction materials: A review”, *Ecol. Eng.*, **36**(2), 118-136.

Espinoza, D., Kim, S. and Santamarina, J.C. (2011), “CO_2 geological storage — Geotechnical implications”, *KSCE. J. Civ. Eng.*, **15**(4), 707-719.

Gong, J. P., Katsuyama, Y., Kurokawa, T. and Osada, Y. (2003), “Double-Network Hydrogels with Extremely High Mechanical Strength”, *Adv. Mater.*, **15**(14), 1155-1158.

Gray, M., Yeung, A., Foght, J. and Yarranton, H.W. (2008), “Potential microbial enhanced oil recovery processes: a critical analysis”, paper presented at SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, 21-24 September, Denver, Colorado, 114676.

Haszeldine, R. S. (2009), “Carbon Capture and Storage: How Green Can Black Be?” *Science*, **325**(5948), 1647-1652.

Holder, G. D., Kamath, V.A. and Godbole, S.P. (1984), “The potential of natural gas hydrates as an energy resource”, *Annu. Rev. Energy*, **9**(1), 427-445.

Holtzman, R. and Juanes, R. (2011), “Thermodynamic and hydrodynamic constraints on overpressure caused by hydrate dissociation: A porescale model”, *Geophy. Res. Lett.* ***38***, L14308.

House, K.Z., Schrag, D.P., Harvey, C.F. and Lackner, K.S. (2006), “Permanent carbon dioxide storage in deep-sea sediments.” *P Natl. Acad. Sci. USA*, **103**(33), 12291-12295.

Huang, M., Kennedy, J.F., Li, B., Xu, X. and Xie, B.J. (2007), “Characters of rice starch gel modified by gellan, carrageenan, and glucomannan: A texture profile analysis study”, *Carbohydr. Polym.*, **69**(3), 411-418.

Inagaki, F., Kuypers, M. M. M., Tsunogai, U., Ishibashi, J., Nakamura, K., Treude, T., Ohkubo, S., Nakaseama, M., Gena, K., Chiba, H., Hirayama, H., Nunoura, T., Takai, K., Jørgensen, B. B., Horikoshi, K. and Boetius, A. (2006), “Microbial community in a sediment-hosted CO_2 lake of the southern Okinawa Trough hydrothermal system”, *P. Natl. Acad. Sci. USA*, **103**(38), 14164–14169.

IPCC (2005), “Special Report on Carbon Dioxide Capture and Storage”, In: Metz., B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L.A., (eds.), Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

Ivanov, V. and Chu, J. (2008), “Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ”, *Rev. Environ. Sci. Biotechnol.*, **7**(2), 139-153.

Jaiswal, P., Al-Hadrami, F., Atekwana, E.A. and Atekwana, E.A. (2014), “Mechanistic models of biofilm growth in porous media”, *J. Geophys. Res. Biogeosci.*, **119**(7), 1418-1431,doi:10.1002/2013JG002440.

Jenneman, G., Lappan, R. and Webb, R. (2000), “Bacterial profile modification with bulk dextran gels produced by in-situ growth and metabolism of Leuconostoc species”, *Soc. Petrol. Eng. J.*, **5**(04), 466-473.

Khachatoorian, R., Petrisor, I.G., Kwan, C.C. and Yen, T.F. (2003), “Biopolymer plugging effect: laboratory-pressurized pumping flow studies”, *J. Pet. Sci. Eng.*, **38**(1–2), 13-21.

Kim, A.R., Cho, G.C. and Kwon, T.H. (2014). “Site characterization and geotechnical aspects on geological storage of CO_2 in Korea”, *Geosci. J.*, **18**(2), 167-179.

Kim, H.S., Oh, T.M. and Cho, G.C. (2015), “P-wave velocity estimation of unconsolidated sediments containing CO_2”, *Int. J. Greenh. Gas. Con.*, **33**, 18-26.

Kirkland, C.M., Hiebert, R., Phillips, A., Grunewald, E., Walsh, D.O., Seymour, J.D. and Codd, S.L. (2015), “Biofilm Detection in a Model Well-Bore Environment Using Low-Field NMR”, *Ground. Water. Monit. Remediat.*, **35**(4), 36-44.

Koide, H., Takahashi, M., Tsukamoto, H. and Shindo, Y. (1995), “Self-trapping mechanisms of carbon dioxide in the aquifer disposal”, *Energ. Convers. Manage.*, **36**, 505-508.

Koide, H., Takahashi, M, Shindo, Y., Tazaki, Y., Iljima, M., Ito, K., Kimura, N. and Omata, K. (1997), “Hydrate formation in sediments in the sub-seabed disposal of CO_2”, *Energy*, **22**(2), 279-283.

Kuhs, W. F., Genov, G., Staykova, D. K. and Hansen, T. (2004), “Ice perfection and onset of anomalous preservation of gas hydrates”, *Phys. Chem. Chem. Phys.*, **6**(21), 4917-4920.

Kvenvolden, K.A. and Lorenson, T.D. (2010), *A Global Inventory of Natural Gas Hydrates Occurrence*, http://walrus.wr.usgs.gov/globalhydrate.

Kwon, T.H. and Ajo-Franklin, J.B. (2013), “High-frequency seismic response during permeability reduction due to biopolymer clogging in unconsolidated porous media”, *Geophysics*, **78**(6), EN117-EN127.

Kwon, T.H., Cho, G.C. and Santamarina, J.C. (2008), “Gas hydrate dissociation in sediments: Pressure-temperature evolution”, *Geochem. Geophy. Geosy.*, **9**, Q03019.

Kwon, T.H., Oh, T.M., Choo, Y., Lee, C., Lee, K.R., and Cho, G.C. (2013), “Geomechanical and thermal responses of hydrate-bearing sediments subjected to thermal stimulation: Physical modeling using a geotechnical centrifuge”, *Energy & Fuels*, **27**(8), 4507-4522.

Kwon, T. H., Song, K. I., and Cho, G. C. (2010), “Destabilization of marine gas hydrate-bearing sediments induced by a hot wellbore: A numerical approach”, *Energy Fuels*, **24**(10), 5493-5507, doi: 10.1021/ef100596x.

Lappan, R. E. and H. S. Fogler (1996), “Reduction of porous media permeability from in situ Leuconostoc mesenteroides growth and dextran production”, *Biotechnol. Bioeng.*, **50**(1), 6-15.

Makogon, I.F. (1977). *Hydrates of hydrocarbons,* Pennwell Books.

Mark, J.E., Erman, B. and Eirich, F.R. (1994). *Science and technology of rubber*, Academic Press, San Diego.

Milkov, A.V. (2004), "Global estimates of hydrate-bound gas in marine sediments: how much is really out there?", *Earth-Sci. Rev.*, **66**(3), 183-197.

Minke, G. (2007), "Building with earth-30 years of research and development at the University of Kassel", *Proc., International Symposium on Earthen Structures, Bangalore, Interline Publishing*.

Mitchell, J.K. and Santamarina, J.C. (2005), "Biological considerations in geotechnical engineering", *J. Geotech. Geoenviron.*, **131**(10), 1222-1233.

Momber, A. (2004), "Wear of Rocks by Water Flow", *Int. J. Rock Mech. Min. Sci.*, **41**(1), 51-68.

Morales, V.L., Parlange, J.Y. and Steenhuis, T.S. (2010), "Are preferential flow paths perpetuated by microbial activity in the soil matrix?", *J. Hydro.*, **393**(1), 29-36.

Moridis, G.J. (2003), "Numerical Studies of Gas Production From Methane Hydrates", *SPE J.*, **8**(04), 359-370.

Moridis G.J. and Reagan, M.T. (2007), "Strategies for Gas Production From Oceanic Class 3 Hydrate Accumulations", paper presented at *Offshore Technology Conference*, *Am. Assoc. of Pet. Geol.*, Houston, Texas, 30.

Moridis, G.J., Collett, T.S., Boswell, R., Hancock, S., Rutqvist, J., Santamarina, C., Kneafsey, T., Reagan, M.T., Pooladi-Darvish, M., Kowalsky, M., Sloan, E.D. and Coh, C. (2013), "Gas hydrates as a potential energy source: state of knowledge and challenges", *Advanced Biofuels and Bioproducts*, Springer Science+Business Media, New York, 977-1033.

Nakayama, A., Kakugo, A., Gong, J.P., Osada, Y., Takai, M., Erata, T. and Kawano, S. (2004), "High Mechanical Strength Double-Network Hydrogel with Bacterial Cellulose", *Adv. Funct. Mater.*, **14**(11), 1124-1128.

Nimblett, J. and Ruppel C. (2003), "Permeability evolution during the formation of gas hydrates in marine sediments", *J. Geophys. Res.*, **108**(B9), 2420.

Noh, D.H., Ajo-Franklin, J.B., Kwon, T.H. and Muhunthan, B. (2016), "P and S wave responses of bacterial biopolymer formation in unconsolidated porous media", *J. Geophys. Res. Biogeosci.*, **121**(4), 1158–1177.

Oh, T.M. (2012), *Rock Excavation using Abrasive Waterjet*, Ph.D. Dissertation, Department of Civil and Environmental Engineering, KAIST, Daejeon, Republic of Korea.

Oh, T.M., Cho, G.C. and Ji, I.T. (2013), "Effects of Free Surface using Waterjet Cutting for Rock Blasting Excavation", *J. Korean Tunn. Undergr. Space Assoc.*, **15**(1), 49-57.

Pawar, R. J., Zyvoloski, G. A., Tenma, N., Sakamoto, Y. and Komai, T. (2005), "Numerical simulation of laboratory experiments on methane hydrate dissociation", *Proc., 15th International Offshore and Polar Engineering Conference*, June, Seoul, Republic of Korea.

Phillips, A.J., Lauchnor, E., Eldring, J., Esposito, R., Mitchell, A.C., Gerlach, R., Cunningham, A.B. and Spangler, L.H. (2012), "Potential CO_2 leakage reduction through biofilm-induced calcium carbonate precipitation", *Environ. Sci. Technol.*, **47**(1), 142-149.

Pires, J.C.M., Martins, F.G., Alvim-Ferraz, M.C.M. and Simoes, M. (2011), "Recent developments on carbon capture and storage: An overview", *Chem. Eng. Res. Des.*, **89**(9), 1446-1460.

Rebata-Landa, V. and Santamarina, J.C. (2012), "Mechanical effects of biogenic nitrogen gas bubbles in soils", *J. Geotech. Geoenviron.*, **138**(2), 128-137.

Rochelle, C.A., Camps, A.P., Long, D., Milodowski, A., Bateman, K., Gunn, D., Jackson, P., Lovell, M.A. and Rees, J. (2009), "Can CO_2 hydrate assist in the underground storage of carbon dioxide?", *Geol. Soc. S.P.*, **319**(1), 171-183.

Santamarina, J.C. and Cho, G.C. (2011), "Energy geotechnology", *KSCE. J. Civ. Eng.*, **15**(4), pp.607-610.

Sherwood, P.T. (1993). *Soil Stabilization with Cement and Lime*, HMSO, London.

Stern, L.A., Circone, S., Kirby, S.H. and Durham, W.B. (2001), "Anomalous preservation of pure methane hydrate at 1 atm", *J. Phys. Chem.*, **B105**(9), 1756-1762.

Summers, D.A. (1995). *Waterjetting Technology*, London, E & FN Spon.

Tang, J., Tung, M.A. and Zeng, Y. (1997), "Gelling Properties of Gellan Solutions Containing Monovalent and Divalent Cations", *J. Food Sci.*, **62**(4), 688-692.

Taylor, S.W. and Jaffé, P.R. (1990), "Biofilm growth and the related changes in the physical properties of a porous medium: 3. Dispersivity and model verification", *Water Resour. Res.*, **26**(9), 2171-2180.

Tohidi, B., Yang, J., Salehabadi, M., Anderson, R. and Chapoy, A. (2010), "CO_2 Hydrates Could Provide Secondary Safety Factor in Subsurface Sequestration of CO_2", *Environ. Sci. Technol.*, **44**(4), 1509-1514.

United Nations General Assembly (2005), "2005 World Summit Outcome", *United Nations*, *Report A/60/1*.

van Paassen, L.A., Daza, C.M., Staal, M., Sorokin, D.Y., van der Zon, W. and van Loosdrecht, M.C. (2010), "Potential soil reinforcement by biological denitrification", *Ecol. Eng.*, **36**(2), 168-175.

Wang, J. (2003). *Abrasive Waterjet Machining of Engineering Materials*, Switzerland, Trans Tech Publications Ltd.

Whiffin, V.S., van Paassen, L.A. and Harkes, M.P. (2007), "Microbial carbonate precipitation as a soil improvement technique", *Geomicrobiol. J.*, **24**(5), 417-423.

White, D. (2009), "Monitoring CO_2 storage during EOR at the Weyburn-Midale Field", *The Leading Edge*, **28**(7), 838-842.

Wu, Y., Surasani, V.K., Li, L. and Hubbard, S.S. (2014), "Geophysical monitoring and reactive transport simulations of bioclogging processes induced by Leuconostoc mesenteroides", *Geophysics*, **79**(1), E61-E73.

Yakimets, I., Paes, S.S., Wellner, N., Smith, A.C., Wilson, R.H. and Mitchell, J.R. (2007), "Effect of Water Content on the Structural Reorganization and Elastic Properties of Biopolymer Films: A Comparative Study", *Biomacromolecules*, **8**(5), 1710-1722.

Yang, F., Zhang, B., Pan, C. and Zeng, Y. (2009), "Traditional mortar represented by sticky rice lime mortar—One of the great inventions in ancient China", Sci. China Ser. E., **52**(6), 1641-1647.

Youssef, N., Elshahed, M.S. and McInerney, M.J. (2009), "Microbial processes in oil fields: culprits, problems, and opportunities", *Adv. Appl. Microbiol.*, **66**, 141-251.

Zeng J. and Kim T.J. (1996), “An Erosion Model of Polycrystalline Ceramics in Abrasive Waterjet Cutting”, *Wear*, **193**(2), 207-217.