# GEOTECHNICAL FUNDAMENTALS IN THE FACE OF NEW WORLD CHALLENGES

## TOPIC AREA: *MULTI-PHYSICS AND MECHANICS*

Humanity faces unprecedented challenges due to population growth[1], increasing energy demand[2], and degradation of ecosystems[3]. In this context, immediate threats come from (i) the consumption of natural resources at rates that hinder the availability of energy supplies, and (ii) the deterioration of the climate to a point that communities are exposed to growing risks of extreme events[4]. To address such crises, a key role is played by geotechnologies[5], i.e. large-scale interventions on near-surface and/or underground deposits for purposes of energy recovery (e.g., hydro-fracture), environmental remediation (e.g., disposal of $CO_2$ and radioactive waste), and risk management (e.g., protection of cities and/or coastal areas from sea level rise and natural hazards). In this context, major challenges derive from the multi-physics of geological systems, as well as from the coupling of the mechanical, hydrologic, chemical and biological properties of the materials that constitute them.

Geomaterials are indeed porous, discrete and heterogeneous media exposed to interactions with the environment[6]. These solids host multiple fluids, with which they establish physico-chemical interactions. As a result, natural and human-induced fluctuations in environmental conditions change their strength and deformation properties, playing a key role in a number of applications, as the forecasting of geohazards, the management of aging infrastructures, and the underground storage of by-products. The literature provides several examples of critical events initiated by multi-physical agents. An example likely to play a remarkable role in the near future is the generation of seismic events due to underground activities, such as $CO_2$ sequestration[7]. Indeed, if this activity is to contribute to the mitigation of the effects of climate change, it has to be pursued at very large scale[8]. Nevertheless, concerns have been raised about pervasive fault reactivation at the injection sites[9], a process that from a geomechanical standpoint is controlled by multi-physical interactions, such as the coupling between fluid flow, dissolution/precipitation of mineral species, fault weakening and frictional instabilities[10]. It is then apparent that the threat of fault reactivation requires an improved understanding of the multi-physics of failure, as these events might undermine the integrity of $CO_2$ repositories and put at stake enormous public investments. Numerous examples can be listed also in the domain of failure processes triggered by natural causes of soil weakening. A famous example due to hydrologic forcing is the Aberfan disaster[11], i.e. the collapse of a poorly compacted spoil tip in the UK. On the morning of 21 October 1966, after several days of rainfall, a subsidence of about 3-6 meters occurred on the upper flank of the partially saturated waste, causing the fluidization of more than 150,000 cubic meters of waste. The fluidized debris flowed downhill at high speed, running over a local school and causing 144 casualties. Similar flow failures occur systematically in several areas of the world, and have the potential to affect both artificial earthworks[12] and natural settings[13]. Similar to the case of underground pressurization, the instabilities leading to such solid-to-fluid transitions are controlled by the simultaneous change in pressures and volume fractions of the pore fluids, as well as by the associated deterioration in soil strength[14].

It can be argued that, unless the physical processes that control such complex failures are explained, limited progress can be achieved in predicting the onset of hazardous situations. Indeed, in the examples above hydrologic, chemical and thermal fluctuations act simultaneously, complicating the interpretation of large-scale failures. In some processes, failure is driven by natural events[15] and involves different deformation mechanisms (e.g., localized slips of flows). In these circumstances, engineers and scientists must predict the onset of a given instability, or at least quantify its probability of occurrence[16]. In other cases, failures compromise the success of technological activities in underground deposits. In addition to the case of carbon-dioxide sequestration, a prominent example is the leakage of hazardous products from the sealing barriers of nuclear repositories[17]. Finally, in other applications failures can be beneficial to productivity[18], making it a desired process (e.g., hydraulic fractures). Nevertheless, also in such applications it is crucial to benefit from models and monitoring techniques to control rate of development and spatial distribution of the activities. Despite the availability of studies tackling similar classes of multi-physical processes, the last decades of research have produced few works able to frame these problems in the context of soil stability and multi-physics[19,20]. Thus, the practice relies exclusively on conventional interpretation methods that are valid only for uncoupled mechanical problems. For these reasons, a major challenge for future decades is to formulate innovative models to quantify the risk of failure due to multi-physical agents, link theories with multi-scale characterization methods and use such tools for interpretation and/or prediction purposes. Hereafter, some knowledge gaps pertaining this area of geotechnology are briefly outlined.

*Knowledge Gap #1*: Multi-physical agents are well-known triggers of inelastic strains. A classic example is *wetting collapse*, i.e. soaking-induced compaction of unsaturated soils[21]. Similar processes are caused by heating (e.g., thermal collapse of clays[22]) or chemical agents (either fluid substitution or mineral dissolution[23]). In geomechanics such events are modeled by a degradation of the yielding threshold based on non-mechanical variables. While the phenomenology of these processes is known, their mechanical interpretation is not straightforward. Indeed their nature has encouraged the use of the term *collapse*, invariably related with the concept of stability. Nevertheless, such processes take place prior to failure, making their interpretation ambiguous without recourse to specific mechanistic theories. In unsaturated soils, in particular, wetting-collapses have been a major reason for questioning the validity of the effective stress principle, i.e. the cornerstone of classical soil mechanics. In other words, although several authors have tried to frame collapse events in mechanical theories, the nature of these processes is still quite elusive. As a result, their physics can be elucidated only by addressing some key questions: (i) Are wetting-collapses (or other forms of non-mechanical compaction) unstable events? (ii) Can they be framed in a mathematical theory of material stability? (iii) Can such mechanisms be explained in light of classical postulates (e.g., an enhanced effective stress principle)?

*Knowledge Gap #2*: Failures caused by non-mechanical agents have ambiguous connotation also in other contexts, as the initiation of flow failures[24]. Extensive studies have shown that compressible fluids alter the threshold for liquefaction both under both monotonic and cyclic loading[25]. Such observations have inspired a variety of methods to mitigate liquefaction[26]. Nevertheless, the state of a porous medium evolves dramatically with environmental processes (e.g., tidal waves, gas release, fluid injection/extraction, frictional heating, gas-pressurization, etc.) and is a primary cause of failures. It is therefore crucial to frame the effect of evolving non-mechanical states into predictive theories to quantify such rapidly moving stability thresholds. In addition, in analogy with the collapse of fluid-saturated soils, volumetric collapses induced by non-mechanical agents are often treated as diffuse modes of failure. However, several basic questions can be asked on this matter. For instance, what is the role of non-mechanical variables in the patterns of failure? Does a change in degree of saturation promote a transition from diffuse to localized failure? Indeed, several studies show that suction-induced embrittlement and localization are quite common in unsaturated soils[27]. This has been seen via biaxial tests or by simulating localization via numerical techniques. Although observed and/or simulated localization processes exhibit patterns very similar to those of saturated porous media[28], experiments and simulations are rarely inspected with bifurcation criteria specialized to variably saturated states[29]. These ideas contain the seeds of a potential adaptation of the bifurcation theory to multi-phase porous media and can pave the way to the enhancement of predictive failure analyses in multi-physical contexts.

*Knowledge Gap #3*: The physical properties of geomaterials are usually randomly distributed in space[30]. While in some cases the heterogeneity is reflected macroscopically by a weak noise of their response, in other circumstances the randomness of the state variables is a source of unstable deviations from homogeneity. Material imperfections are in fact a recognized trigger of localized instabilities. When multi-physical processes are considered, however, non-mechanical state variables are a further source of heterogeneity and, hence, of additional weakness[31]. As a result, the spatial variability of these variables, as well as their evolution during transient processes, is an important constraint to localized and/or diffuse instabilities. A challenge for geomechanics research during the next decades will therefore be the adaptation of theoretical, experimental computational techniques to study the multi-physical processes that exacerbate the potential for instability and, hence, that alter our understanding of failure thresholds.

*Knowledge Gap #4:* Multi-scale cross-couplings influence the non-linear dynamics of geo-systems, and should be accounted in the equations that control the evolution of geological deposits. Multi-phase flow, thermal fluctuations, and chemical reactions interact with the rate and magnitude of collapse, comminution, and faulting. Conversely, deformation of the porous medium alters permeability, pore fluid flow, and reaction kinetics. Such couplings are usually treated in an empirical way via porosity-permeability criteria and pressure-dependence laws for creep strains. However, the results of semi-empirical models are scale dependent and not transferable to general geological settings, and it is not possible to perform experiments for all the combinations of microstructural properties and site conditions encountered at the field scale. Improved fundamental descriptions are needed to link local and up-scaled properties, and to support predictions needed for design of engineering strategies. It is then arguable that the possibility to track the evolution of these properties during loading, flow, and reaction should rely on models including microstructural descriptors and providing a physical basis to the coupling terms of reaction-transport-deformation laws.

*Knowledge Gap #4*: Laboratory studies have elucidated that evolving microstructure and chemical composition affect remarkably macroscopic properties[32]. While numerous multi-physical models have been proposed to capture these mechanisms, most of them are phenomenological and do not include microstructural attributes. Hence, such approaches are valid only for a relatively narrow range of conditions. For example, many analyses rely on macroscopically defined conductivity, retention properties and reaction-kinetic constants. Such properties are subject to changes due to dilation, compaction, crushing and fracture. Although phenomenological models are useful to capture specific phenomena under fixed states, they have limited predictive capacity for evolving states. Thus, there is a tremendous need for approaches able to relate micro- and macro-scale properties and predict the effect of an evolving microstructure. As a result, a key challenge for the foreseeable future is to formulate a new generation of models incorporating microstructural descriptors and capturing physical couplings as emergent properties due to micro-scale interactions[33].

*Knowledge Gap #6:* Continuum laws rely on a representative elementary volume (REV), whose size must be sufficiently large compared to the length scale of the microstructure. While this definition is crucial for capturing the salient aspects of geomaterial behavior at large scales, coupled physical-chemical processes can cause irreversible deformations of the matrix (either diffuse or localized[34]), as well as force redistribution and transformation of material via fluid-solid interactions. The microstructure is therefore subject to changes that alter the REV size and affect the interpretation of tests. In addition, different properties, like permeability, reaction rates, and rock compressibility, are typically associated with different REVs. This aspect prevents a unified upscaling and causes strong-scale dependencies of the results. The coupling of mechanical and non-mechanical processes has recently been observed in fluid imbibition in multiphase granular systems[35]. X-ray imaging has revealed a loss of homogeneity during fluid injection in multi-phase granular media, suggesting the impossibility to define an REV based on a standard laboratory sample. This problem was exacerbated by pore-scale heterogeneity and deformation bands. Similar phenomena are likely to occur during reactive transport and/or thermal forcing, as local thermal gradients, flow velocities, and reaction kinetics control the redistribution of mass and net (upscaled) transformation rates. Several key questions can be asked on this matter: (i) How do reactive transport, solid-fluid couplings, and thermal fluctuations alter the REV for usual geotechnical properties? (ii) Do geotechnical tests adequately represent the properties of geomaterials?

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# Multiscale Procedures in Geomechanics: Applications to Plasticity, Liquefaction and Fracking

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ABSTRACT: This whitepaper highlights some of the current interests of the Computational Geomechanics Group in the Civil and Mechanical Engineering Department at Caltech. The overarching theme of the group is using multiscale methods to remove as many phenomenological models as possible from continuum methods. The phenomenological models are replaced, typically, with grain-scale mechanics and microscale physics. In this whitepaper, we exemplify three main areas of application and research: plasticity, liquefaction, and hydraulic fracking.

## INTRODUCTION

In the last few decades, geomechanics as a field has experienced a shift towards multiscale methods, which aim to connect the grain scale (mm) to the engineering scale (>m). Advances on both ends of the spectrum have motivated this shift through continuum models such as plasticity and particle models such as the discrete element method (DEM) (Cundall et al., 1979). Similarly, experimental methods have migrated from the continuum scale such as triaxial compression/extension to grain scale experiments equipped with micron-resolution imaging (Hall et al., 2010). Figure 1 shows an example of the collection of modeling tools (modeling campaign) and experimental tools (characterization campaign). The engineering motivation comes from planetary exploration, but it is applicable to other areas such as civil engineering, defense, etc.

This white paper will focus on three application areas with a high potential for development of multiscale techniques that can help bypass empiricism and aid engineering analysis. We will focus on plasticity as a basic modeling tool; prediction of liquefaction phenomena in sands; and hydraulic fracture for fluid injection and extraction in geologic formations. In all of these areas, we look at the grain scale, the continuum scale, and the multiscale approach as a means of getting the best accuracy at the lowest possible implementation cost. This paper is organized into the grain scale section, the continuum scale section, and the multiscale section, while touching on each of the three areas of application.

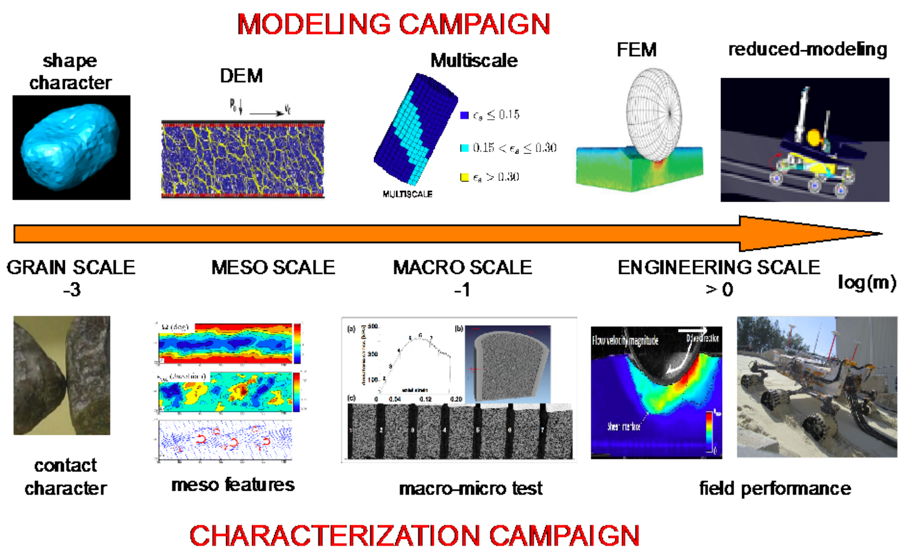


**FIG. 1. Modeling and experimental paradigms captured by multiscale methods.**

GRAIN SCALE APPROACH

A common approach in grain scale mechanics is DEM, which models individual grains as rigid particles that interact with each other through Newtonian mechanics. DEM has been used effectively to capture the complex plastic deformations (shear bands, etc.) in granular materials. However, the approximation of grain morphologies, typically with geometric shapes (spheres, triangles, etc.), discards some of the important underlying grain scale physics, potentially limiting DEM's effectiveness. Recent advances in experimental approaches seek to remedy this issue using X-ray computed tomography (XRCT) to capture the exact grain morphology (Hall et al., 2010). This capability has led to extensions to DEM, namely level set DEM (Kawamoto, In Submission) that use XRCT data to model the exact grain geometries, improving the simulation of grain scale physics.

The grain scale approach has also become popular of late for analyzing liquefaction at the lab scale. DEM provides a way to track the behavior of individual grains, helping researchers understand how the collective granular behavior manifests itself at the macroscale. It has helped show how grain scale quantities like coordination number, fabric anisotropy, and grain shape can affect liquefaction behavior (Lim et al., 2014). Various research groups have also proposed coupling DEM with the Lattice Boltzmann method (LBM) to encapsulate fluid behavior during liquefaction.

DEM also provides an effective means for modeling heterogeneities and fractures in hydraulic fracturing reservoirs at the grain scale. In DEM models, reservoirs are represented by a network of discrete elements connected by various types of bonds, depending on the material and type of heterogeneity. Fracturing is modeled explicitly as broken bonds, which allows for crack nucleation, crack propagation, and coalescence with other cracks.

In summary, the grain scale approach is ideal for understanding the fundamental mechanics and underlying behavior of granular materials; however, it is prohibitively expensive when it comes to modeling field scale phenomena.

## CONTINUUM SCALE APPROACH

Classical continuum plasticity is a common method for simulating the plastic behavior of granular materials. The key feature is the choice of constitutive model (Mohr-Coulomb, Drucker-Prager, Cam-Clay, etc.), which dictates the macroscopic mechanics. Essentially, such models are all driven by phenomenology. Although these models are powerful, they tend to lack physics, limiting their applicability in modeling granular materials outside of experimental datasets.

The continuum approach has proven to be very useful when it comes to investigating and modeling liquefaction failure on the field scale. Flow liquefaction triggering is commonly modeled at the instant when the second order work of the material becomes zero. The second order work criterion has inspired the development of other continuum criteria that help investigate the mechanics at the onset of liquefaction. For instance, flow liquefaction triggering has been shown to coincide with the plastic hardening modulus reaching a critical value (Andrade, 2009), or the vanishing of the symmetric part of elasto-plastic constitutive tangent (Borja, 2006), which gives further insight into the mechanics of liquefaction. The continuum modeling approach has also proven useful when it comes to developing liquefaction charts to assess earthquake-induced liquefaction susceptibility in the field.

Continuum approaches are also useful in hydraulic fracturing, where the success of practices in the field depend on understanding the complex interaction between fracture processes and the surrounding environment. We recently developed a reliable simulation tool for modeling hydraulic fracture using the extended finite element method (XFEM) with the cohesive crack model. This innovative approach for numerical modeling of fluid-driven fractures allows us to faithfully account for the different physical phenomena involved in hydraulic fracturing. These physical phenomena include: flow of the fracturing fluid within the crack, deformation of the porous medium, and the development of micro-cracking and nonlinear fracture processes in the reservoir.

In summary, continuum approaches offer the ability to model field scale phenomenon for many different applications. A disadvantage is their inherently empirical nature and calibration with a limited number of experimental datasets.

## MULTISCALE APPROACH

Multiscale approaches seek to take the mechanics from the grain scale and use those to bypass phenomenological laws in classical continuum models at the field scale combining the best of both approaches. Recent advances in multiscale methods (Andrade et al., 2011) achieve this by calculating continuum model parameters (friction coefficient, plastic dilatency) with DEM and passing them up to continuum methods. This method allows the physics of grain scale mechanics to reach field scale applications. Other recent work (Lim et al., 2015) extends these methods by modeling individual grains with digital avatars to capture exact particle morphology, improving the quality of the grain scale physics simulations.

Liquefaction can also be modeled using a multiscale approach. For instance, as the material approaches liquefaction triggering, a multiscale approach can be activated. A recipe would involve projecting an imposed strain increment onto a unit cell, and using DEM computations to obtain the stress response. This in effect would bypass the phenomenological laws used to obtain the elasto-plastic tangent. If fluid behavior were included, then the material permeability would be calculated using LBM, rather than the phenomenological equations.

In hydraulic fracturing reservoirs, the formation of micro-cracks ahead of the physical crack tip creates an ideal candidate for multiscale analysis. Within a multiscale framework, macroscopic cracking is modeled using XFEM with a cohesive law obtained from a grain-scale simulation. The near tip fracture processes are modeled at the granular level with DEM, while taking into account the underlying heterogeneities. The information derived from the grain scale computation is then recast in the form of a cohesive law to the continuum scale.

## CONCLUSIONS

Geomechanics research has seen a rapid progression over the last few decades. Grain scale approaches are continually being improved and with increased computational power, more grains can be simulated. Continuum approaches have also been refined and improved with insight from cutting edge experimental techniques and theoretical work. However, both grain scale and continuum scale approaches will continue to have their disadvantages. Current and future multiscale methods will blend the best of both approaches and continue to push the boundaries of geomechanical engineering design and analysis. In this paper, we highlighted a few applications (plasticity, liquefaction, hydraulic fracking), but many more will be investigated with these exciting techniques in the coming years.

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# Geotechnical Characterization of Hydrate-Bearing Sediments

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**ABSTRACT:** Methane gas hydrate, a potential energy resource and also s risk to global climate, is found massively in marine and permafrost sediments worldwide. Extensive data on fundamental geotechnical properties of sediments containing gas hydrate (or hydrate-bearing sediments) have been obtained primarily using laboratory synthesized specimens. Pressure core techniques allow enhanced understanding of naturally occurred hydrate-bearing sediments. Unsolved geotechnical issues of hydrate-bearing sediments include geomechanical and hydrological behaviors during hydrate dissociation, improved pressure core and in situ testing techniques, and enhanced understanding on hydrate deposits in response to man-made (drilling and production) disturbances and environmental changes.

## INTRODUCTION

Methane gas hydrate, which physically resembles ice, is a crystalline compound of methane gas and water. The stability of gas hydrate requires relatively low temperature and high pressure conditions, which limit the occurrence of methane hydrate in nature primarily in marine continental margin sediments and beneath permafrost. Methane gas hydrate in nature contains the largest amount of carbon on earth, is a potential energy resource, risks climate change and global warming, and potentially affects large-scale seafloor stability. Extended studies on gas hydrate started since 1930s and the publication grows exponentially through the 20$^{th}$ century; however, research on hydrates in sediments (or hydrate-bearing sediments) has emerged only in recent two decades (Figure 1).

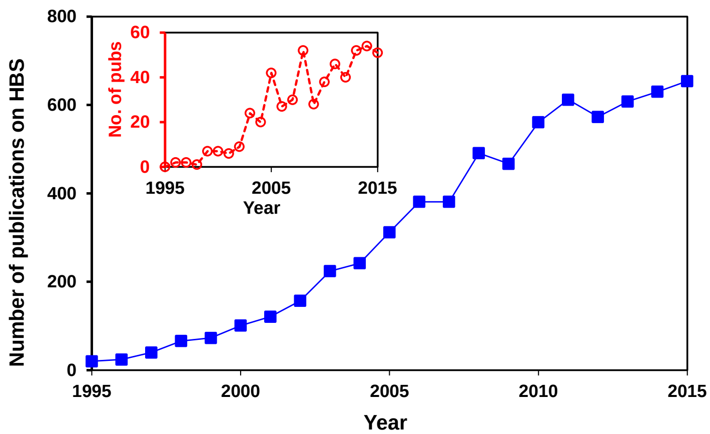



**FIG. 1. The number of annual publications on hydrate-bearing sediments (HBS). The inset shows the number of publications with 'hydrate-bearing sediments' in the title. Data are compiled through Google Scholar.**

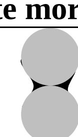
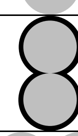
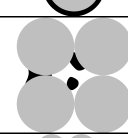
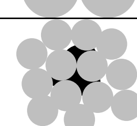
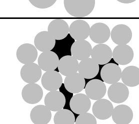
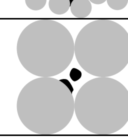
## PREVIOUS STUDIES AND ACCOMPLISHMENTS

*Formation methods and hydrate pore habit*

Hydrate formation in sediments in nature is mainly from dissolved methane in water saturated systems (Buffett and Zatsepina 2000), thus hydrate has no preferential nucleation site on grain contacts or gas-water interfaces in an unsaturated system that typically used in the lab (Waite et al. 2009). The morphology of naturally occurred hydrate in sediments is inherently governed by the relative magnitude of skeleton force versus hydrate-water interfacial force (Dai et al. 2012, Clennell et al. 1999).

Laboratory formation of methane hydrate in sediments using the dissolved gas method (Waite and Spangenberg 2013) is time consuming due to low methane gas solubility in water, i.e., 0.02g/kg under standard condition. Many expedient methods using unsaturated systems with excessive gas, however, result in particular hydrate pore habits depending on experimental procedures (Table 1). Recent studies observe hydrate pore habits and morphology in sediments through direct visualization (Spangenberg et al. 2014) and X-ray computed tomography at pore- (Seol et al. 2015, Ta et al. 2015, Kerkar et al. 2009) and core-scales (Kneafsey et al. 2007, Seol and Kneafsey 2009, Rees, Priest and Clayton 2011). The visualization of hydrate pore habits in sediments covers only few laboratory formation methods and no direct pore-scale visualization of naturally occurred hydrate-bearing sediments has yet been obtained.

**Table 1. Laboratory Methods of Forming Hydrate-Bearing Sediments**

| Methods | | Illustration of possible hydrate morphology |
|---|---|---|
| Unsaturated system | Unsaturated soils: pressurization→saturation |  |
| | Moist sands: freeze→thaw→pressurization<br>freeze→pressurization→thaw |  |
| | Sand-ice mixture: pressurization→thaw |  |
| | Unsaturated soils: saturation→pressurization |  |
| Saturated system | Saturated soil: pressurization→gas injection |  |
| | Soil saturated with dissolved gas in water |  |

*Fundamental physical properties*

*Mechanical properties*. Enhanced understanding on the mechanical behavior of hydrate-bearing sediments is attributed to the understanding of hydrate pore habit, which dramatically affects the sediment's stiffness (Yun et al. 2005, Priest, Rees and Clayton 2009) and strength (Jung, Santamarina and Soga 2012, Ebinuma et al. 2005, Masui et al. 2005). The mechanical behavior of naturally occurred hydrate-bearing sediments from Nankai Trough follows the pore-filling model at low hydrate saturations ($S_h$<20-30%) and the load-bearing model at high hydrate saturations (Santamarina et al. 2015, Yoneda et al. 2015). Comprehensive studies on the mechanical properties of hydrate-bearing sediments use THF as hydrate former in various types of sediments (Yun, Santamarina and Ruppel 2007, Lee et al. 2010a). Challenges remain in the properties characterization during hydrate dissociation (Hyodo et al. 2013, Lee, Santamarina and Ruppel 2010c, Waite et al. 2008, Kneafsey et al. 2011a), constitutive (Uchida, Soga and Yamamoto 2012, Sultan and Garziglia 2011, Lin, Seol and Choi 2015) and coupled modeling (Sanchez et al. 2010, Rutqvist and Moridis 2007, Kwon, Song and Cho 2010).

*Thermal properties*. Since the thermal conductivity of hydrate is similar to that of water, the bulk thermal conductivity of saturated hydrate-bearing sediments is marginally affected by hydrate saturation but dominated by stress state, grain size, and packing (Cortes et al. 2009, Waite et al. 2002, Henninges, Huenges and Burkhardt 2005). The presence of gas complicates the system's thermal properties (Dai et al. 2015). Current studies have failed to investigate the thermal behavior of hydrate-bearing sediments during dynamic hydrate dissociation process, in which phase transformation (from solid to liquid and gaseous phases) may associates with grain migration and fabric change.

*Electromagnetic properties*. Current studies on electromagnetic properties of hydrate-bearing sediments includes comprehensive laboratory measurement of THF hydrate in various types of sediments (Lee, Santamarina and Ruppel 2010b), fundamental theories (Lee et al. 2010b), and pore-scale analytical models (Spangenberg 2001, Spangenberg and Kulenkampff 2006). Recent interpretation of electrical resistivity logging in hydrate deposits considers anisotropy and fractured medium (Cook et al. 2010, Cook et al. 2012).

*Hydraulic properties*. Laboratory measurement of single-phase (water) permeability in hydrate-bearing sediments is limited (Jaiswal 2004, Johnson, Patil and Dandekar 2011, Kneafsey et al. 2011b, Daigle, Cook and Malinverno 2015). Measurement of water permeability in natural samples without dissociating hydrate is extremely rare (Santamarina et al. 2015, Konno et al. 2015). Existing models for water permeability in hydrate-bearing sediments can consider effects of hydrate pore habit and core-scale heterogeneity (Dai and Seol 2014, Kleinberg et al. 2003). Multiphase flow (i.e., gas and water) in hydrate-bearing sediments has been studied only numerically (Jang and Santamarina 2014, Mahabadi and Jang 2014).

*Laboratory and field testing techniques*

Geotechnical characterization of hydrate-bearing sediments in the laboratory include triaxial (Yoneda et al. 2013, Hyodo et al. 2005, Masui et al. 2005, Winters et al. 2004, Yun et al. 2007), resonant column (Priest, Best and Clayton 2005), oedometer (Lee, Santamarina and Ruppel 2008), and permeameter tests (Seol, Choi and Dai 2014, Johnson et al. 2011). Numerous natural sediments from hydrate deposits have been remolded and characterized after synthesizing methane, carbon dioxide, and THF hydrates within the sediments (Lee et al. 2008, Winters et al. 2004, Winters et al. 2011, Dai, Lee and Carlos Santamarina 2011, Lee et al. 2011, Kim and Yun 2013, Masui et al. 2008).

With the development of pressure core testing techniques (Yun et al. 2006, Santamarina et al. 2012, Schultheiss, Holland and Humphrey 2009) that allow geotechnical characterization of naturally occurred hydrate-bearing sediments without dissociating hydrate, hydrate-bearing pressure cores from worldwide hydrate deposits have been studied including Gulf of Mexico (Yun et al. 2006), Ulleung Basin (Yun et al. 2011), Krishna-Godavari Basin (Yun, Fratta and Santamarina 2010, Rees et al. 2011), and Nankai Trough (Santamarina et al. 2015, Yoneda et al. 2015, Konno et al. 2015).

*Submarine instability*

Hydrate stability is achieved only under certain pressure and temperature conditions. Warming ocean temperatures (or changes in current patterns) trigger hydrate dissociation (Phrampus and Hornbach 2012) and further provokes gas migration and landslides (Kvenvolden 1999), including one of the largest submarine landslides the Storegga Slide in Norwegian offshore (Vogt and Jung 2002). Hydrate dissociation induces excess pore pressure, volume expansion, and significant reduction in sediment strength, leading to geomechanical instability (Grozic 2010, Nixon and Grozic 2006, Nixon and Grozic 2007, Sultan 2007, Xu and Germanovich 2006). The mechanism of progressive failure of hydrate deposits due to creep susceptibility (Booth, Silva and Jordan 1984, Mountjoy et al. 2013, Mountjoy et al. 2014) remains elusive since rheological properties of hydrate-bearing sediments are not yet obtained. Submarine instability of hydrate deposits in response to environmental change should be evaluated under sea level rise in thousand-year time scale and anthropogenic warming in decadal time scale scenarios.

## CHALLENGES AND RESEARCH NEEDS

*Fundamental properties during hydrate dissociation*

Gas production from hydrate involves phase change, volume expansion, heat transfer, and multiphase flow. Extensive studies in the past decades have gained in-depth understanding on many physical, hydrological, and geomechanical properties of hydrate-bearing sediments. Yet, these fundamental properties and the hydro-thermal-mechanical coupled processes during dynamic hydrate dissociation remain elusive.

*Sampling and in-situ testing*

Improved understanding on sampling disturbances to natural hydrate-bearing sediments and pressure cores. Improved tools for recovering, testing, and in-situ characterization of hydrate-bearing sediments and reservoirs. Constitutive models based on experimental results of never-depressurized natural cores.

*Hydrate-bearing clayey sediments*

More than 90% of natural gas hydrates are trapped in fine-grained sediments. Yet, hydrate-bearing clayey sediments is the least understood and characterized. Future research needs to seek in-depth understanding of hydrate formation mechanisms, laboratory synthetization methods, fundamental physical properties, and engineering and geological implications of hydrate-bearing clayey sediments.

*Spatial variability and upscaling*

Enhanced understanding on hydrate formation in sediments considering the effects of hydrate formation process on hydrate pore habit and ensued properties of hydrate-bearing sediments. Visualization and tomography techniques to reveal these processes in natural sediments and understand the impacts of sediments characteristics (e.g., fine grains) and heterogeneity at various scales. Effective characterization and evaluation methods for heterogeneity at various scales; innovative inversion theories considering multi-scale heterogeneity and upscaling techniques.

*Commercially viable gas production*

Research conducted by the industry and DOE has provided a good understanding of the geo-hazards associated with the short-term risks of drilling through hydrates (DOE 2016). The major remaining near-term challenge, that will likely make (sand-enclosed) gas hydrates an exploitable resource, is how to engineer such deposits to produce gas at the rates necessary to make expensive deep-water production commercially viable. The key is to assure sufficient heat transfer and continuous fluid/gas flows during the depressurization of hydrate reservoirs. Fundamental research and technology barriers include evaluation and prediction of multiphase (i.e., water, gas, hydrate, fines, and sands) flow, management of sand production and fines migration, and identification of geological and physical constraints on sufficient heat transfer and gas supply.

*Long-term behavior under global warming scenario*

Effective laboratory methods of forming representative hydrate-bearing sediments in a timely manner. Creep and time-dependent responses of hydrate-bearing sediments that can shed light on creep deformation caused progressive failures in large scale. Mechanisms of slope stability and seafloor settlement (pockmark) caused by hydrate dissociation and/or dissolution. Reservoir behavior due to man-made disturbances (e.g., drilling, gas production, other hydrocarbons recovery) and under various global warming scenarios.

## CONCLUSIONS

Current understanding on hydrate-bearing sediments still largely depends on laboratory studies of synthesized specimens under static conditions. Numerous geotechnical issues associated with hydrate-bearing sediments, e.g., fundamental properties, flow processes, sampling disturbance, site characterization, production strategies, and slope instability, remain unsolved. Further research needs to address the hydro-thermo-mechanical coupled process during hydrate dissociation, improved laboratory visualization and testing techniques, development of site monitoring and characterization methods, and in-depth understanding of submarine instability of hydrate deposits due to drilling or ocean temperature increase at various spatial and temporal scales.

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