40th IGS Lecture

Novel Techniques to Simulate and Monitor Contaminant-Geomaterial Interactions

Dr. Devendra Narain Singh (dns)
Institute Chair Professor
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai-400076
dns@civil.iitb.ac.in
ORCID ID: 0000-0003-3832-1507
Dr. Devendra Narain Singh  FNAE, F-ASCE, FICE(UK)
Institute Chair Professor
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai, India-400076
dns@civil.iitb.ac.in
www.civil.iitb.ac.in/~dns

Dr. D. N. Singh was born in 1965 at Shahjahanpur, UP, India. He has been a faculty member of Civil Engineering at Indian Institute of Technology Bombay, since 1994. Before joining IIT Bombay he has served Central Road Research Institute, New Delhi, and Indian Institute of Technology Kharagpur, for short durations. His early education was completed at Lucknow, UP, India. He obtained his bachelor’s, masters and Doctoral degrees from IIT Kanpur in 1986, 1989 and 1993, respectively.

His teaching, and research and developmental activities are in quite diversified areas of geotechnical engineering (viz., soil mechanics, foundation engineering, environmental geotechnology, mechanics of unsaturated soils, soil characterization based on thermal and electrical properties, contaminant transport in porous media, mineralogical characterization, utilization and recycling of industrial waste, geotechnical centrifuge modeling, etc.). He has published 285 technical articles of which 199 are in the refereed journals. He has supervised 36 Doctoral (and 7 ongoing) dissertations and 35 Masters theses. He has been successful in filing 19 (Indian) and 1 US patents and 3 have been granted.

Apart from teaching and research, Dr. Singh has been very actively associated with some of the most prestigious business houses, as an in-house instructor and retainer consultant. He has taken up sponsored projects from Bhabha Atomic Research Centre (BARC), Indian Council of Agricultural Research (ICAR), Department of Science and Technology (DST-TIFAC), All India Council of Technical Education (AICTE) and Atomic Energy Regulatory Board (AERB). With financial aids received from these and several other organizations, he has established a state-of-the-art Environmental Geotechnology Laboratory in the department.
Dr. Singh has founded *Environmental Geotechnics*, ICE Publishing, London, UK, and has been its *Editor-in-chief*. He has been ‘Editorial Board Member’ of several journals of repute. He is recipient of *Young teachers’ award* instituted by the AICTE, New Delhi and *JUNIOR/SENIOR Paper Award* from the *International Association for Computer Methods and Advances in Geomechanics (IACMAG)* for the year 2005. He was *Chairman, 12th IACMAG, GOA, India, 1-6 October 2008*.

He is recipient of *Excellent Contributions Award 2008*, which is given by the IACMAG to individuals who have a record of significant contributions in research, academic activities and professional service in different regions of the globe. He is recipient of *John R. Booker Excellence Award-2011*, which is given by the IACMAG for *advancement of research, education and practice of Environmental Geotechnology and development of novel techniques to simulate contaminant transport in geomaterials, under laboratory and in-situ conditions*. He is recipient of *Richard Feynman Prize 2014*, for the best paper published by the *ICE journal*.

Dr. Singh is Fellow of:

1. Indian National Academy of Engineering, New Delhi
2. American Society of Civil Engineers (ASCE) and
3. Institution of Civil Engineers (ICE), London, UK
Abstract:

Generation of huge amount of the toxic & hazardous wastes coming out of various industrial and domestic activities is becoming a major threat to the society. In the long-run, mainly because of non-scientific storage, disposal and closure, and due to the presence of undesirable concentration(s) of chemicals and radio-nuclides, elevated temperatures and microbial activity, these wastes (read contaminants) interact with geomaterials viz., soils, rock mass, ground-water. This interaction, termed as contaminant-geomaterial interaction, depending upon the severity of the contaminant(s) and interaction time, might alter overall characteristics of the geomaterials. Unfortunately, conventional laboratory and field instrumentation techniques are not well equipped to capture such interaction(s) and the mechanisms that prevail in the geomaterials. Hence, to achieve these objectives, evolving adequate and workable strategies, and modalities, that are nondestructive, noninvasive and economical is desirable. In this context, author’s association with several industries resulted in development of innovative, cost-effective, yet efficient techniques that facilitates laboratory and/or in-situ simulation and monitoring of such interaction(s). Details of these techniques, the philosophy behind their creation and the way they can be employed for safeguarding geoenvironment, from deterioration, are presented and discussed in this paper. Also, a brief discussion on some of the real-life situations where such techniques can be applied easily, by suitably modifying them, is presented for the benefit of the aspiring researchers and professionals.

Keywords: Geoenvironment, toxic and hazardous waste, waste disposal, contaminant, geomaterial, interaction, instrumentation, monitoring, simulation.
1. Introduction

Various industries, considered as the backbone of a nation and responsible for making it powerful and self-reliantviz., manufacturing, pharmaceutical, oil & gas exploration, thermal power plants, atomic power generation, research & medication installations, dredging and mining, generate huge amountof hazardous and/or toxic waste (Singh, 2014; Rao et al., 2014; Bo, 2015; Hoyos et al., 2015; Rajesh et al., 2015; Rowe, 2014, 2015). Furthermore, activities like agriculture, construction & demolition, and ‘domestic discharges’ are responsible for generation tremendous amount of the municipal solid waste, MSW. Keeping in view the sustainable growth, ideally, strategies to utilize such waste, as a man-made resource, should have been practiced (Arulrajah, 2015; Tripathy, 2015). In this context, it is heartening to note that these issues are being recognized by the researchers, planners, industries and the administration as a major threat for the society (Jayanthi and Singh, 2016; Koshy and Singh, 2016a,b; Jayanthi et al. 2017; Ganaraj and Singh, 2017; Shetty and Singh, 2017, 2018), and ready-to-adopt techniques that have potential to overcome this situation, are being developed, marketed and implemented.

However, in order to safeguard the ecosystem against the wrath of such a situation, the waste, which might inherently contain leachable heavy metals and radionuclides, designated as contaminants, should be isolated from the geoenvironment by proper containment, encapsulation, immobilization, vitrification and/or disposal in deep geological formations (IAEA, 2004). An easy way to visualize the geoenvironment is to think of the subsurface domain, the geomicrobiological sphere, that mainly comprises the soil and rock mass, microorganisms and ground-water (Reddy, 2015; Pathak et al., 2014a,b, 2016a,b; Johnstonand O’Kelly, 2016; Rakesh et al., 2017). In the long-run, these contaminants, due to their interaction with the rain-water and/or fluctuating ground-water table, which act as a nemesis for the units (read canisters in case of the radionuclides) in which the waste is contained, tend to contaminate the geoenvironment (Marti, 2015; Benson, 2016).

Incidentally, attributes like chemical activity, high temperatures and the presence of radionuclides, in contaminants, and inherent characteristics of the geomaterials viz., mineralogy and the presence of organic matter, pose a great challenge in evolving a proper and workable strategy to deter geoenvironmental degradation. To add to this list of woes, which makes this situation more complex, but realistic, the microbial (bacterial, fungal, pathogenic, viral and algal) activities pose a major threat to the
geoenvironment. Incidentally, the author; a geotechnical engineer who as a student was averse to biology, was induced to take up this challenge by bio-savvy and enthusiastic young researchers (Sharma and Singh, 2015; Sharma et al., 2016; Shashank et al., 2016, 2018; Sowmya et al., 2017; Meenu et al., 2017). Another challenge being faced, in this context, is the multi-phase state of geomaterials, which makes it not-so-easy task to simulate and monitor the influence of contaminants on geomaterials and the mechanisms prevailing in them (Dangayach et al., 2015; Joseph et al., 2016, 2017). From this discussion, it can be realized that handling, storage and disposal of toxic and hazardous wastes, and identifying/establishing their impact on the geoenvironment (by conducting environmental impact assessment, EIA) is becoming an utmost priority (Gurumoorthy and Singh, 2004a, b; Gurumoorthy and Singh, 2005, Rakesh et al., 2009; Rao et al., 2008, Arnepalli et al., 2010, Hanumantha Rao et al., 2013).

For safe execution of geotechnical engineering projects, various laboratory and field instrumentation techniques and testing protocols that facilitate characterization of geomaterials have already been developed. And this knowledge has also been adopted and prescribed by various statutory agencies such as FHWA (Federal Highway Administration, USA), ASTM (American Society for Testing and Materials) International, USA, BS (British Standards), EC (Eurocode), BIS (Bureau of Indian Standards) and EPA (Environmental Protection Agency), in the form of codal-provisions. These protocols are quite useful to capture macro-characteristics of geomaterials viz., strength, compressibility and hydraulic conductivity, which are mainly driven by mechanical stresses (better designated as stimuli), only. However, for a situation like contaminant-geomaterial interaction, picturized above, capturing micro-mechanisms viz., diffusion, dispersion, sorption and desorption, decay/decomposition, deposition, erosion and suffusion, exo- and endo- thermic reactions, heat and moisture migration, cracking, rheology and coupling of these mechanisms, becomes very crucial (Goreham and Lake, 2018). Needless to state, these mechanisms are driven by environmental factors viz., humidity, temperature, solar cycle, wind speed and rainfall intensity, and might evolve due to chemical, thermal, electromagnetic, radiation and microbial activities. These factors can be designated as environmental stimuli and their influence on overall characteristics (physical, chemical, mineralogical and biological) of the geomaterials and the mechanisms that prevail in them, should be investigated rigorously when contaminant-geomaterial interaction occurs (Kadali et al., 2013a, b, 2014, 2016). Needless to emphasize, all this falls beyond the realm of the conventional geotechnical
methodologies and techniques and hence resorting to an interdisciplinary approach becomes inevitable (Kibsgaard, 2016).

Furthermore, the situation becomes dire when reputed and established equipment manufacturers shy away in extending their helping hand to the research fraternity, due to several reasons and constraints viz., lack of interest, inertia to adopt and practice new concepts, fear of not fulfilling supply-demand chain, lack of financial viability, etc. However, this turned out to be a blessing in disguise and prompted the author and his research group (designated as THE ENVGEOS) to deal with simulation and monitoring contaminant-geomaterial interaction. This incidentally, was the starting point of our journey in the realm of geoenvironmental engineering (Singh, 2016). A brief account of the research & development contributions made by THE ENVGEOS, in context of simulating and monitoring short- and long-term contaminant-geomaterial interaction and the prevailing mechanisms, is presented in the following. In due course of time, these techniques, which are a trendsetter, indigenous, economical and ingenious, became a panacea for solving various geoenvironmental issues, highlighting the fact that there is nothing called a Problem, it’s just absence of an idea to find, the Solution.

2. Types of Contaminant-Geomaterial Interaction

Based on the above discussion, it becomes imperative that efforts should be made to simulate, and quantify, contaminant-geomaterial interaction, which would be very useful for addressing various geoenvironmental issues that the contemporary society is facing, in a precise manner. The changes undergone by the geomaterials, when contaminants (exhibiting attributes like elevated temperatures, chemical and radio-nuclide concentrations) interact with them. This would be quite important and crucial for designing structures such as liners of waste containment facilities, landfills, cores of the dam, which are primarily constructed from fine-grained soils, treatment and stabilization of highly contaminated soils and dredged sediments, stabilization of soft & sensitive soils, and construction of roads & airfields by resorting to thermal treatment (Rowe, 2015; Zhang et al., 2011; Shetty and Singh, 2017).

The possible situations when contaminant-geomaterial interaction are: (1) passive geomaterial interacting with water, which corresponds to minimal interaction viz., sands-water interaction, (2) active-geomaterial interacting with water viz., fine-grained soil-water interaction, which could result in heat of wetting, HOW, (3) passive
geomaterial interacting with contaminants viz., sands-contaminant interaction, and (4) active geomaterial interacting with contaminants, viz., fine-grained soil-contaminant interaction. These interactions might occur, in geoenvironment either due to natural or man-made activities. Hence, the effect of these activities on overall properties of the geomaterials (pre- and post-interaction) should be investigated (Sreedeep and Singh, 2005a, 2006a, 2011). In this context, though, researchers have employed various techniques and instrumentation viz., batch tests, column tests, lysimetric studies, geotechnical centrifugemodeling and impedance spectroscopy, to monitor and quantify contaminant-geomaterial interaction, under controlled environmental conditions, most of these studies are contaminant and geomaterial specific and hence cannot be generalized, especially when soils are exposed to higher concentrations and temperatures associated with the contaminants.

2.1 Quantification by using $k_d$ Parameter

The contaminant-geomaterial can be quantified by employing a parameter, designated as distribution coefficient, $k_d$. It has been demonstrated by Arnpalli et al. (2010), Pathak et al. (2014a,b) that several parameters viz., specific surface area, SSA, cation exchange capacity, CEC, percentage organic matter, percentage of fines, CL, mineralogy, redox potential, type of ionic species and their concentration, pH, temperature, liquid to solid ratio, L/S, and interaction time, influence determination of $k_d$, which requires very intricate experimental investigations. Hence, design of the batch tests to minimize the experimental efforts, and to understand the influence of so many parameters on $k_d$, becomes most desirable. Also, due to interplay of these parameters, it becomes difficult to identify the parameter(s) which would have most significant influence on $k_d$. It should be noted that identification of such parameter(s) would be helpful in optimizing the number of tests to be conducted for determining $k_d$ of a contaminant-soil system, CSS, which otherwise is a very cumbersome task. To achieve this, Taguchi method, which primarily helps in designing experiments (Taguchi and Konishi, 1987) was employed for (i) identification of the most significant parameters on which $k_d$ depends and (ii) estimating $k_d$ by inputting these parameters, in the form of a lookup table, which would be quite handy for all those who design and analyze different types of CSSs, as described in the following.

Various soils such as White clay (designated as WC), Bentonite (designated as BT), five natural soils namely S1, S2, S3, SS1, and SS2, collected from different parts of
India, were used. Further, SrCl₂, CaCl₂, CdCl₂, HgCl₂, ZnCl₂, FeCl₃, NiCl₂, and nitrates of Thorium, Uranium, Lead, and Cobalt in their non-radioactive form, were employed as the model contaminants. Batch tests were conducted following the guidelines presented in literature (ASTM D4646-03, 2008; Arnepalli et al., 2010) and various sorption/desorption isotherms were employed to compute the respective $k_d$(Pathak et al., 2014a,b). The effect of concentration of contaminants on $k_d$ was standardized by employing electrical conductivity, $\sigma$, of the some of the contaminant-soil solutions during sorption and desorption processes, as depicted in Fig. 1. The data depicted by solid and open symbols, in the figure, correspond to sorption and desorption processes, respectively, for various CSSs.

It can be observed from Fig. 1 that, as expected, $\sigma$ increases with an increase in initial concentration, $C_i$, of the contaminants used in the study. This highlights the fact that the contaminant contributes more in the value of $\sigma$ of the CSS as compared to the soil.

![Fig. 1. Variation of electrical conductivity after sorption and desorption for different CSSs.](image)
However, the reverse phenomenon takes over when $\sigma$ of the CSS increases due to leaching of the cations present in the soil, when it interacts with the lower concentration of the contaminant. These facts can be elaborated further by employing a term critical concentration or critical molarity, $M_{crt}$, depicted as a vertical dotted lines in Fig. 1. Incidentally, this line demarcates contribution of soils towards desorption (marked as a left side arrow, when soil is dominating in the CSS) and sorption mechanisms (marked as a right side arrow, when contaminant is dominating in the CSS). Hence, it can be opined that the concentration of the contaminant plays a very crucial and decisive role in determination of $k_d$ of the CSS. As such, establishment of $M_{crt}$ by conducting batch tests with a wide range of concentration of contaminants and determining the sorption mechanism prevailing in a certain concentration range of contaminant, becomes mandatory to obtain meaningful $k_d$. To establish the influence of $C_i$ on $k_d$, three cases of the $\sigma$ versus $C_i$ relationship (refer Fig. 2), which also exhibit the $M_{crt}$, were considered. These cases are: (i) $C_{FULL}$, (ii) $C_{Mcr-Min}$ and (iii) $C_{Max-Mcr}$, as depicted in Fig. 2, where $C_{FULL}$, $C_{Mcr-Min}$ and $C_{Max-Mcr}$ exhibit concentration ranges from 0.5 to $1 \times 10^{-7}$ M, $M_{crt}$ to $1 \times 10^{-7}$ M and 0.5 M to $M_{crt}$, respectively.

![Fig. 2. The three cases of the initial concentrations of the contaminant considered for determination of the $k_d$](image)

Furthermore, kinetic and thermodynamic studies for various CSSs were conducted on soils BT, WC, S1, S2, S3 and contaminants SrCl$_2$, Pb(NO$_3$)$_2$ and UO$_2$(NO$_3$)$_2$), which are the major isotopes present in radioactive waste, by performing batch tests. The kinetic reaction depends upon the interaction between the sorbate-sorbent (i.e., the contaminant-soil) system (Azizian, 2004), which also helps in determining the changes in the concentration of the sorbate over a certain duration. As such, the
sorption rate of the contaminants onto the soil particles (i.e., the sorption mechanism) was also studied. As temperature is an important factor that influences the sorption characteristics of the soil (Wang, 2011), batch tests were performed by varying temperature, $T$ (viz., 27±2°C, 35±2°C and 45±2°C) while, the interaction time of CSS, $L/S$, soil $pH$, soil and contaminant species were maintained unchanged. The thermodynamic studies were performed to understand (i) how energy changes and/or dissipates in the CSS and (ii) the nature of reaction (i.e. spontaneous or non-spontaneous) within this system.

As mentioned earlier, Taguchi method was used to design batch tests by employing L25 orthogonal array, $OA$, referred by Taguchi and Konishi (1987) and Wu and Zhou (2011), which is a special matrix having optimal setting of maximum six parameters and minimum two parameters with five setting levels (i.e., the experimental conditions). It is based on the selection of the five parameters in the study (refer Table 1).

Table 1. Selection of the input parameters and experimental conditions

| S.N. | $L/S$ (M) | $C_i$ (M) | Contaminant | $CEC$ (meq/100g) | $pH_i$ |
|------|-----------|-----------|-------------|-----------------|--------|
| 1    | 10        | 0.1       | SrCl$_2$    | 105.05          | 1      |
| 2    | 20        | 0.02      | CaCl$_2$    | 82.41           | 3      |
| 3    | 50        | 0.003     | CdCl$_2$    | 77.39           | 5      |
| 4    | 100       | 0.0005    | Pb(NO$_3$)$_2$ | 54.58              | 6      |
| 5    | 200       | 0.0001    | HgCl$_2$    | 37.59           | 7      |

However, it should be realized that for investigating the influence of these five parameters on $k_d$, $5^5$ (=3125) experiments need to be conducted, which turns out to be a mammoth task. This necessitates establishment of sensitivity of the $k_d$ on the various attributes of the soil-contaminant system, as discussed above. Such a sensitivity analysis would be helpful in minimizing the number of experiments, otherwise required, to determine $k_d$. Moreover, for investigating the influence of these parameters on $k_d$, a wide range of experimental conditions were chosen for quantifying the contaminant-soil interaction. Subsequently, batch tests were designed for five different parameters and five experimental conditions, as mentioned in Table 1. Accordingly, L25 $OA$ was found suitable, and only 25 batch tests were performed.
for understanding the mutual influence of the five parameters. Based on this analysis, a lookup table (refer Table 2) for various CSSs was also developed. The lookup table is a quick interface for estimating $k_d$ for different types of contaminant-soil systems, and can be utilized for proper design and execution of various geoenvironmental projects mentioned earlier.

The efficiency of the lookup table should be verified for several contaminant-soil systems by conducting batch tests. The methodologies based on electrical and microwave impedances should be developed for determination of $k_d$, a panacea for detecting the influence of the waste on the geoenvironment.

Table 2. The “Lookup Table”

| Soil | pH | CL | SSA | $CEC_T$ | RWL | Minerals | MO | $\xi$ | Cationic species | $pH$ | T | $T_e$ | $k_d$ (l/kg) |
|------|----|----|-----|---------|-----|----------|----|------|----------------|------|----|------|-------------|
| BT   | 7.5| 90 | 621 | 105     | 33.80 | M        | 4.27| 33.50| U, Th, Pb, Cd | 3    | 4  | 6    | 12          |
| WC   | 54 | 49 | 38  | 48.63   | K    | 3.62     | 17.50|       | Ca, Sr, Co, Zn| 4    | 5  | 24   | 36          |
| S1   | 6.2| 31 | 23  | 82      | 56.55 | Ma, Mu   | 10.60| 14.50| Fe, Ni, Hg    | 5    | 6  | 36   | 48          |
| S2   | 5.2| 70 | 21  | 64      | 70.18 | Mu, Bi, Mil | 1.60| 24.89|                 |      |    |      |             |
| S3   | 7.1| 44 | 289 | 61      | 83.48 | Mu       | 2.94 | 12.50|                 |      |    |      |             |
| SS1  | 7.3| 0  | 629 | 77      | 42.73 | Q, He, Ma | 4.55| 19.21|                 |      |    |      |             |
| SS2  | 7.8| 0  | 279 | 55      | 29.78 | Q, C     | 7.66 | 27.51|                 |      |    |      |             |

Note: CL: clay fraction (in %); SSA: specific surface area (in m$^2$/g); $CEC_T$: Total cation exchange capacity (in meq./100g); $\xi$: Zeta potential (in -mV); RWL: Reactivity with lime (in %); MO: Summation of CaO, K$_2$O and Na$_2$O (in %); $T$: temperature (in °C); $T_e$: Interaction time (in hr.); M: Montmorillonite; K: Kaolinite; Ma: Magnetite; Mu: Muscovite; Bi: Biotite, Mi: Mullite; Q: Quartz, He: Hematite; C: Calcite

2.2 Quantification by using XRD, Nano-indentation and LSDTechniques

Kadali et al. (2013a) attempted to: (a) develop a methodology, which can be employed for quantifying contaminant-soil interaction, under laboratory conditions, and (b) investigate the changes undergone by the soil, when it interacts with the contaminants (possessing both high temperature and concentration). To achieve this, the state-of-
the-art instrumentation and techniques viz., laser scanning diffraction, X-ray diffraction stress analysis and nano-indentation have been employed. Such a study has been found to be very handy to develop a soil characterization scheme, based on the parameters that imbibe physical, chemical and mineralogical characteristics of the soil, and can easily and quickly be determined in any conventional geotechnical engineering laboratory, as described in the following.

The mechanical and engineering characteristics (such as hardness, residual modulus, and resistance to indentation) of the geomaterial were determined up to 200 °C, in steps of 50 °C, by employing a nano-indenter (Model: TI 900 TribolIndenter, marketed by Hysitron, USA). This equipment contains a CCD camera, attached to an optical microscope (refer Fig. 3a). A Berkovich indenter, refer Fig. 3b, which is a three-sided pyramid of radius of curvature ∼150 nm and measures the force imposed on the pellet (read specimen, refer Fig. 3c), was employed for these investigations. The corresponding displacements are recorded with the help of LVDTs.

The investigations conducted by Kadali et al. (2013a) have revealed that the changes in the color of soils, heated up to 250 °C, can be attributed to depletion of the organic matter, primarily (Ulery and Graham, 1993; Parlak, 2011). However, corresponding to the temperatures greater than 250 °C, except for the soils containing kaolinite, this phenomenon could be attributed to an increased oxidation and other chemico-mineralogical changes (Kadali et al., 2013b). An increase in the specific gravity and decrease in the specific surface area, SSA, of the soil, due to its exposure to elevated temperatures, has also been observed. This phenomenon can be attributed to the loss of moisture, presence of the organic matter, impurities and changes occurring at...
elemental level. It has also been observed that, except for the soils with passive minerals viz., quartz and kaolinite, the clay-sized fraction decreases while the silt-sized fraction increases with an increase in temperature. This observation further substantiates that exposure of the soil to elevated temperatures results in an increase in its particle size. The decrease in the SSA of the soil can further be substantiated by an increase in its particle size due to its exposure to elevated temperatures, as substantiated by laser scanning diffraction analysis. Interestingly, it has been observed that the cation-exchange capacity, CEC, of the soil decreases as the exposure temperature increases. This can be attributed to a reduction in the exchangeable cations and loss of organic matter present in the soil (Cox et al., 2000; Simkovic et al., 2008). Furthermore, a reduction in zeta potential (West and Stewart, 1995; Vane and Zhang, 1997; Yukselenand Kaya, 2003; Kaya and Yukselen, 2005; Akbulut and Arasan, 2010; Moayedi et al., 2011) of the soil, which defines its capacity to interact with the environment (read water, air, gases, contaminants), due to its exposure to elevated temperatures and excess contaminant concentrations, has also been observed (Chorom and Rengasamy, 1996; Ketterings et al., 2000; Abu-Zreig et al., 2001; Hatten et al., 2005; Liu, 2010; Yilmaz, 2011). The investigations by employing X-ray diffraction were instrumental in demonstrating, successfully, that with an increase in exposure temperature, \( \theta \), the lattice spacing changes (refer Fig. 4), which indicates mineralogical phase transformation.

Here it is worth reiterating that the changes in crystallographic characteristics of the geomaterial would strongly influence its physical and chemical properties. It has also been observed that with an increase in temperature, the soils containing passive
minerals viz., quartz and kaolinite, exhibit expansion. On the contrary, soils containing active minerals viz., montmorillonite, shrink, due to the loss of hygroscopic moisture (Shah and Singh, 2006; Prakash et al., 2016). Furthermore, the investigations conducted by Kadali et al. (2014) were instrumental in demonstrating the utility of X-ray Diffraction analysis for establishing residual normal and shear stresses on the soil grains when they get exposed to the elevated temperatures (Tanaka et al., 1997; Sultan et al., 2002; Tan et al., 2004; Welzel et al., 2005). These researchers were also successful in demonstrating the potential of nano-indentation, which is mostly employed by material scientists for characterization of metals, in identifying the changes undergone by the fine- and coarse-grained soils when they get exposed to elevated temperatures (Penumadu et al., 2009; Daphalapurkar et al., 2011). A typical load versus displacement response of a soil exposed to different temperatures is depicted in Fig. 5.

Based on our studies, we could also demonstrate that the fine-grained soils, in contrast to the coarse-grained soils, are more susceptible to changes in hardness, $H$, residual modulus, $E_r$, and resistance to indentation, $h_{\text{max}}$, when exposed to elevated temperatures (refer Fig. 6). However, efforts should be made to extend these studies by considering (a) the interaction of different types of contaminants and geomaterials of entirely different species, exposed to elevated temperatures, (b) quantification of such interaction and derivation of generalized relationships and (c) investigations related to the alteration in various geotechnical properties of the soils (viz., shear strength, compressibility, compaction characteristics, permeability etc.) due to such interaction(s).
Fig. 6. Variation of the (a) hardness, (b) residual modulus and (c) maximum depth of indentation with respect to temperature for a typical soil

2.3 Quantification by using Heat of Wetting

As mentioned earlier, the heat of wetting, HOW, is an interesting philosophy to quantify contaminant (in fluid phase) and geomaterial interaction. In case of the fluid that is a liquid, the setup employed for quantifying the HOW would be similar to the one used by professionals that work on cementitious materials & admixtures, i.e., a calorimeter or a heat of hydration setup. However, when the liquid gets replaced with the gas, more intricate setups that would facilitate its adsorption and desorption on the
geomaterials (this process is a precursor to sequestration) need to be created or employed (Rajesh et al., 2015).

The HOW setup, to simulate contaminant-geomaterial interaction when the latter is in liquid form, consists of a calorimeter, which is a wide-mouth vacuum flask of 500 ml capacity, fitted at the top with a cork stopper containing two holes. Through one of these holes, a funnel for pouring the sample in the flask is fitted while the second hole facilitates fitting of a T-type thermocouple, which records temperature of the solution, when connected to a datalogger. The calibration of the thermocouple was carried out by inserting it in boiling water and ice. A stirrer, which is rotated by a motor at a constant speed, has been provided to facilitate proper mixing of the soil and contaminant in the liquid form. This simple setup, has been found to be quite useful for quantifying contaminant-geomaterial interaction, as explained in the following.

As depicted in Fig. 7, the temperature, $\theta$, versus time, $t$, trends for the soils of entirely different chemical constituents, could be utilized for computing the HOW of a geomaterial in its contaminated or uncontaminated states.

![Diagram of temperature versus time for HOW tests](image)

**Fig. 7.** The variation of temperature with time for HOW tests
As depicted in Fig. 7, the $\theta$ versus $t$ trends for the soils can be grouped into three categories: A, B and C, mainly depending upon their characteristics. While, both trends A and B exhibit a sharp increase in $\theta$, in case of the former, temperature attains almost a constant value, $\theta_c$, with time while in case of the latter, it drops down sharply from a peak temperature, $\theta_p$, followed by attainment of the constant temperature value, $\theta_c$. In author’s opinion, these trends, in general, exhibit soil-water interaction, which primarily depends upon the physical, chemical and mineralogical characteristics of the soil (Bathija et al., 2009). However, trend C indicates very less interaction, as the changes in values of $\theta$ are almost negligible. Subsequently, the percentage increase in the temperature of the soil-water mixture, $PIT = (\theta_c - \theta_i) \cdot 100 / \theta_i$, can be computed. It should be noted that $\theta_i$ corresponds to the ambient temperature, for $t=0$ sec. Another parameter, the reaction time, $RT (= t_c - t_i)$, has been defined, which quantifies the minimum time required by the soil-water slurry to attain the constant temperature, $\theta_c$. It is author’s hunch that $RT$ is related to the $PIT$ and hence it should be a measure of the potential of the soil to release heat (due to exo-thermic reaction) when it comes in contact with water. This study demonstrates the utility of the parameter, $HOW$, which has been quantified as the percent change in temperature of the fine-grained soils when they are allowed to interact with water (or for that matter any contaminant in the solution form) in a calorimeter. However, as during this interaction, the physical, chemical and mineralogical properties of soils play an important role, this parameter has been related to various soil specific properties viz., clay fraction present in the soil, $CL$, plasticity index, $PI$, liquid limit, $LL$, specific surface area, $SSA$, and cation-exchange capacity, $CEC$. Based on extensive investigations, on fifty soils of entirely different characteristics, it has been demonstrated that there exists a well-defined relationship between these parameters and the $PIT$, refer Fig. 8 (Kadali et al., 2016).
It is believed that the relationships proposed in Fig. 8 can be employed for determining the soil specific parameters, particularly the fine-grained soils, just by determining the PIT, which can be obtained easily, and quickly, by employing a calorimeter. Needless to mention, this philosophy (read technique) will be a boon for the researchers and professionals dealing with the characterization of soils. However, it is recommended that extensive studies should be conducted, by the research fraternity, to check the validity and utility of the proposed relationships (Fig. 8), and to refine them if they are found misleading. A big leap in this context would be to evolve a novel soil classification system for characterizing the soils by utilizing the parameter PIT, which includes in it the physical, chemical and mineralogical characteristics in a holistic manner.
3. Gas-Geomaterial Interaction

Some good examples of gas-geomaterial interaction are: remediation of contaminated soils by air-sparging (Reddy and Adams, 2001), carbon sequestration (Sarhosis et al., 2018), radioactive waste disposal (Mahjoub and Rouabhi, 2018) and gas permeation in porous media (Rouf et al., 2016). Incidentally, determination of specific surface area, SSA, of geomaterials, by employing: (a) Blaine’s air permeability apparatus (ASTM C 204) and (b) Absorption/Adsorption techniques, wherein Methylene Blue, Nitrogen gas, Ethylene Glycol Monoethyl Ether, EGME and Air, are employed (Arnepalli et al., 2008), is another good examples of gas-geomaterial interaction.

Another challenging but industry-relevant problems that Shanthakumar et al. (2008a,b) studied is flue-gas conditioning, FGC, of the fly ash, as described in the following. It is a well-understood fact that among various pollution control devices, electrostatic precipitators, ESPs, and cyclone separators, are popularly employed by the thermal power stations, and cement plants, for reduction of suspended particulate matter, SPM, as depicted in Fig. 9(a). This is mainly due to their greater efficiency in removing particles (<0.01 µm in size), their effectiveness in a wide range of operating temperatures, and their suitability for corrosive environmental conditions. However, the constraints associated with implementing various measures to enhance performance of ESPs at a power station are: (i) constraints associated with the feed coal (i.e., cost associated with import, washing of the coal and environmental issues associated with it, and ash content etc.), (ii) addition of more collection plate area in the ESP, which requires more space and is highly expensive, (iii) the installation and operating costs for employing wet ESPs is too high apart from lump formation of the ash, and its degradation as a construction material, (Singh and Kolay, 2002a). Under these circumstances, the FGC becomes the inevitable choice, mainly due to the fact that the (i) lower cost input compared to the establishment of additional ESPs, (ii) shorter execution time, (iii) more flexibility and versatility even if variations in operating parameters occur (such as coal variation, boiler load, ESP voltage and current change), SPM levels can be controlled/maintained easily by simply adjusting the amount of FGC agents. These agents are quite useful in reducing resistivity, R, refer Fig. 9(b) and hence improving the surface conduction characteristics of the particles of fly ash/dust (Shanthakumar et al, 2010).
Apart from this, researchers have demonstrated and critically evaluated the importance of the FGC by resorting to different techniques viz., sulphur trioxide conditioning, ammonia conditioning and dual flue gas conditioning, DFGC (Shanthakumar et al., 2009). It has been reported by these researchers that during conditioning of the flue gas, a part of the conditioning agent (particularly ammonia) gets precipitated on the fly ash particles, which might influence its overall characteristics and hence its utility & marketability. The conditioned ash might also lead to contamination of both the ground- and surface- water, if disposed in a landfill.

To answer these issues, comprehensive studies were conducted to investigate the influence of FGC on physical, chemical, mineralogical, morphological and pozzolanic characteristics of the fly ash. Also, how FGC results in improved performance of the ESPs, and hence in a reduction of the SPM emission levels, should be studied extensively keeping in view the intricate gas-geomaterial interaction, which is essential to design and model various environmental clean-up strategies.

In this context, the SEM micrographs of the fly ash (refer Fig. 10), after DFGC, reveal that this treatment is more effective for increasing the fly ash collection due to agglomeration of the ash particles, which enhances the collection efficiency of the ESP. This in turn results in less SPM emissions from the power plants levels (Shanthakumar et al., 2008a,b,2009,2011).
However, the growing emphasis on utilization of the fly ash, and cenospheres, has raised major concerns about the suitability of the conditioned fly ash in cement and concrete industry (Bartake and Singh, 2005, 2007; Das et al., 2011). This is mainly due to the fact that the presence of residual conditioning agent might adversely affect the characteristics of the fly ash. Hence, it becomes essential to ascertain the extent of changes undergone by the fly ash in its physical, chemical, mineralogical, morphological and pozzolanic characteristics, as a result of the FGC. Also, the influence of FGC on the collection efficiency of the ESPs needs to be investigated, which would be of great help in developing a suitable strategy for controlling the SPM emission levels at thermal power stations.

In this context, studies conducted by Shanthakumar et al. (2008a,b, 2009, 2011) turned out to be a big relief, for the power plants. These studies were instrumental in demonstrating that the optimal dose of the conditioning agent(s) does not alter the lime reactivity and pozzolanic activity (Dalinaidu et al., 2007) of the conditioned fly ash.

4. Effects of Contaminant-Geomaterial Interaction

When contaminant-geomaterial interaction occurs, depending upon the severity of this interaction, the geomaterial might undergo: (a) mineralogical alteration and (b) decomposition. These micro-mechanisms might result in fabric alteration of the geomaterial, as well, as explained in the following.
4.1 Mineralogical alteration

One of the good examples of the contaminant-geomaterial interaction is ‘alkali activation’ of the fly ash, which results in mineralogical alteration of the fly ash (Singh and Kolay, 2002a). Hence, apart from many applications of the fly ash, known to the construction industry (Kolay et al., 2001, Kolay and Singh, 2002a,b; Singh et al., 2002), its valorization in the form of ‘fly ash zeolites’, FAZ, has gained significant attention of researchers in the recent past (Kolay and Singh, 2000,2001a, Kolay et al., 2001; Jha and Singh, 2011).

The FAZs viz., Na-P1, hydroxysodalite, faujasite, chabazite, analcime and cancrinite, are available in hydrated alumino-silicate mineral forms and can be synthesized from the fly ash by its adequate alkali activation. However, the physical properties viz., specific gravity, specific surface area, chemical composition viz., silica and alumina contents, and mineralogy viz., quartz and mullite, of the fly ash largely influence this process, the grades of FAZs formed, mostly quantified by the cation exchange capacity, in particular (Kolay and Singh, 2001b; Arnpalli et al., 2008; Bayat et al., 2015). Accordingly, use of fly ash zeolites in industries, especially for removal of heavy metal ions and other wastes for various environmental cleanup projects, would primarily depend upon their grade, which would mainly depend upon the method adopted for the synthesis (Kolay and Singh, 2002a,b; Koshy et al., 2015a,b; Shankara et al., 2016; Koshy and Singh, 2016a). Over the years, several methods: (a) hydrothermal, (b) fusion prior to hydro-thermal treatment, (c) microwave assisted hydrothermal treatment and (d) molten salt technique have been adopted by researchers for achieving the desired mineralogical alteration of the fly ash, read synthesis of ash zeolites, (Jha and Singh, 2011,2012; Koshy and Singh, 2016b; Koshy et al., 2018), as discussed in the following.

To simulate the effect of contaminant-geomaterial interaction on mineralogical alteration of the geomaterial, the mixture of the raw (or original) fly ash, RFA, and different stock solutions of NaOH, was hydrothermally activated at 100 °C, in an open refluxed system, as depicted in Fig. 11. The activation duration was varied from 12 to 48 hours, with an increment of 12 hours (Jha and Singh, 2013,2014a,b). After each step of interaction, the residues and the supernatant were processed and recycled, as depicted in Fig. 12(a). The oven-dried residues from primary treatment, PT, were powdered, with the help of mortar and pestle, before each recycling step, R1 and R2.
Both the residues and supernatant from each step were characterized, simultaneously. On the other hand, the three-step activation, TSA, by fusion of the fly ash, coated with NaOH (NaOH/RFA ratio varied from 0.2 to 1.4, at an increment of 0.2), was conducted at 500 °C for 2 hours, in a Muffle furnace (Jha and Singh, 2014a). To overcome the issues associated with inadequate contact between the RFA and NaOH, fused residues were powdered using mortar and pestle, before subjecting them to recycling steps of fusion, F2 and F3, as depicted in Fig. 12(b).

Fig. 11. Details of the reactor employed for hydrothermal activation of the fly ash

Fig. 12. The stepwise flow charts for the TSA of the fly ash by (a) hydrothermal and (b) fusion methods
The results obtained from these syntheses are presented in Figs.13 and 14. Symbols Q, ML, P, C, S, F, H and M designate the quartz, mullite, zeolite Na-P1, cancrinite, hydroxysodalite, faujasite, hematite and molarity of the NaOH solution, respectively. The designations 1.5-PT, 1.5-R1 and 1.5-R2 correspond to the residues produced after Step-1, 2 and 3 of the TSA, respectively, by using 1.5M NaOH and 12 hours of activation in each step. The formation of polycrystalline phases of the FAZs can be observed in Fig. 13a, which can be attributed to significant gain in the cation exchange capacity, CEC, of the residues (up to 185%) after the Step-2 (refer Fig. 13b). Although, the Step-3 causes less increase in the CEC, remarkable growth in the crystal shapes up to 830 nm (refer Fig. 14a) is indicative of enrichment with hydroxyl bonds and more-Si-O-Al-bonding (confirmed by a shift in the peak depicted in Fig. 14b). This indicates more crystallization in the residues, 1.5-R2 (refer Fig. 14b), as compared to the raw fly ash, RFA, (Eisazadeh et al., 2012; Jha et al., 2015).

Fig. 13. The effect of the TSA on characteristics of the residues, changes in the (a) mineralogy and (b) CEC
Fig. 14. The effect of the TSA on characteristics of the fly ash residues as confirmed from the (a) Morphology of 1.5-R2-24 and (b) FTIR results.

However, efforts should be made to relate the cation exchange capacity of the geomaterial with the silica-alumina ratio. Such a correlation would be very much useful for predicting the susceptibility of a geomaterial to get mineralogically altered. This philosophy would also be useful for the production of synthetic minerals at industrial scale for their application in various environmental clean-up projects.

4.2 Decomposition

The severity of the contaminants, in terms of elevated temperature, the concentration of the chemicals, radionuclides, microorganisms, and environmental radiations are primarily responsible for decomposition of geomaterials that consist of high organic matter viz., humus, peats, marine clays, biochar, municipal solid waste etc. This process might result in generation of leachates, semi-solids and gases, which tend to migrate through the appropriate pathways in the far- and near-fields to contaminate the geoenvironment (Rakesh et al., 2009, 2017). The decomposed geomaterial should be treated as a ‘multi-phase system’ and its conceptualization and modeling is the prime focus of The ENVGEOs, presently, as discussed in the following.

The major factors responsible for controlling the rate of decomposition of the municipal solid wastes, MSW, which author treats as the manmade resource, are the moisture content, temperature and biological activities. To study the degradation characteristics of the MSW, sustainable engineered bioreactor landfill, SEBLF, were
developed. As depicted in Fig. 15, a scaled-down field model of the SEBLF would facilitate: (a) demonstration of the effectiveness of the state-of-the-art instrumentation viz., time and frequency domain reflectometry, TDR & FDR, probes and multi-level thermocouples, that is conceived for monitoring the moisture content and temperature, respectively, (b) to maintain the favorable conditions for bacterial activity, which would accelerate the decomposition rate by controlling the moisture content and temperature of the MSW inside the SEBLF, through scheduling of leachate recirculation, (c) to ascertain the controlled emission (and capturing) of biogas generated due to decomposition of MSW, (d) to analyze the leachate characteristics, which are indicative of the degree of decomposition, over a period of time, and (e) to assess groundwater and surrounding soil contamination (Patil and Singh, 2015; Patil et al., 2017; Chembukavu et al., 2019).

![Diagram of SEBLF setup](image)

**Fig. 15. Installation of the FDR probe and thermocouple in the SEBLF**

To simulate decomposition of the MSW, under laboratory conditions, the (a) laboratory bioreactor landfill, designated as LBLF, (ref. Fig. 16a) and (b) the SEBLF, (ref. Fig. 16b) were developed. These setups have been found to be quite useful for conducting studies related to decomposition of the MSW.
The TDR & FDR probes, and thermocouples were employed for monitoring & controlling the moisture content, $W$, and temperature, $\theta$, at a certain depth in these reactors, respectively (refer Fig. 17). It should be noted that due to the spatial heterogeneity of the MSW, in its composition and density, the application of such probes and interpretation of the obtained results is a challenging task (SushaLekshmi et al., 2018a,b). Through this exercise, it has been realized that by proper scheduling of leachate recirculation (Reddy et al., 2016), the rate of decomposition of the MSW can be augmented up to a great extent (Patil et al., 2017). Furthermore, it has been demonstrated that due to the presence of various macro- and micro- nutrients in the final harvested material (the residues) of the anaerobic and aerobic BLFs could be an appropriate replacement for the conventional manures and fertilizers (Reddy et al., 2003; Patil et al., 2017).

**Fig. 16 (a) Schematic of the (a) laboratory bioreactor landfill, LBLF, and (b) sustainable engineered bioreactor landfill, SEBLF.**

**Fig. 17. Monitoring decomposition of the MSW by employing state-of-the-art instrumentation and leachate recirculation**
However, extensive studies are required, to study the effect of heterogeneity of MSW on the decomposition processes in the bioreactor landfill. Development and application of the low-cost wireless sensors in the bioreactor landfills, which can be used for monitoring the pH, moisture content, temperature, constituents of the biogas and bacterial growth appears to be an idea worth trying. Also, leachate augmentation by treating it with microbes should also be tried.

4.3 Fabric Alteration

Based on the discussion presented above, it is easy to comprehend that when contaminant-geomaterial interaction occurs, the fabric of the geomaterial might get changed (Fan et al., 2017). This is valid particularly for the particulate geomaterials viz., soils mass, which consists of the particles and pores of various sizes and shapes, and their arrangement, nature and distribution is termed as fabric. These parameters, and hence the fabric, influence engineering properties of the soil mass viz., shear strength, compressibility, rheology, conductivity of fluids, etc., to a great extent (Gumaste et al., 2014a,b; Du et al., 2015; Jha and Sivapullaiah, 2016). Hence, quantification of the fabric, and its anisotropy, becomes important for a better understanding of their overall response to external stimuli, particularly in case of the fine-grained soils (Gumaste et al., 2013; Du et al., 2014). In this context, a methodology based on electrical impedance measurement, termed as Impedance Spectroscopy, IS, for determining the fabric of the soil mass in its undisturbed, remolded, sedimented and exposed to thermal flux states was developed (Kaya et al., 2006; Rohini and Singh, 2004; Shah and Singh, 2004, 2005, 2006; Sreedep et al., 2004; Bhat et al., 2007; Gumaste et al., 2014a, b; SushaLekshmi et al., 2016). Incidentally, this methodology has also been found to be extremely useful for quantifying the fabric-anisotropy, as discussed in the following.

The undisturbed samples of the marine clays, were collected from the eastern coast of India, with their depth ranging from 5 to 65 m, below the seabed. To obtain fabric characteristics of these samples, their electrical conductivity, \( \sigma \), was measured across A-A (longitudinal direction) and B-B (transverse direction) as depicted in Fig. 18. The test setup depicted in Fig. 19 was developed and employed for this purpose (Gumaste and Singh, 2010).
Fig. 18. Measurement of the impedance response of the sample on (a) longitudinal (A-A), and (b) transverse (B-B) planes

Fig. 19. The sample holder used for conducting impedance spectroscopy of the sample

Investigations to establish *fabric* of the sample were also conducted by resorting to scanning electron microscopy, SEM, and mercury intrusion porosimetry, MIP, on 5 mm cubical specimens, retrieved from the UDS or reconstituted samples, as depicted in Fig. 20.

Fig. 20. Extrusion of the cubical specimen for establishing its *fabric*
These investigations reveal that fabric of the soil mass, and its anisotropy, could be quantified in terms of the electrical anisotropy viz., the anisotropy coefficient, $A_e$. As such, in case of the soil mass exhibiting flocculated fabric (i.e., the random orientation of the particles) $A_e$ will be equal to (or approaches) unity. On the contrary, in case of the soil mass exhibiting dispersed fabric, the $A_e$ is much higher than unity (>1.75). In case of the undisturbed marine clays, normally, $A_e$ is very high ($\approx 2$) and it almost remains constant with the moisture content. However, in case of the samples retrieved from the same borehole, but from different depths, $A_e$ is found to be strongly dependent on the sampling depth (the overburden). Incidentally, it is possible to classify or identify the type of fabric exhibited by the soil mass based on its $A_e$ value, refer Fig. 21, which presents results obtained from the techniques like IS, SEM and MIP. Fig. 21 can be utilized as a guideline for determining the fabric (i.e., its type and corresponding mean pore diameter, $d_m$) of the fine-grained clays, if $A_e$ is known. Incidentally, it should be appreciated that determination of $A_e$, by adopting the technique mentioned above, is quite easy, and less time consuming, as compared to SEM and MIP techniques.

![Fig. 21. Guidelines for determining fabric of the fine-grained soils](image-url)
Hence, the advantage of IS over MIP and SEM, for determining fabric of the soil mass, in a nondestructive and noninvasive manner, and that too without facing the complexities associated with the sample preparation has been established. It must also be appreciated that the size of the sample and its moisture content are not a constraint for conducting the IS, as compared to its counterparts, and hence the results obtained would be more reliable.

**4.4 Alteration in Geomechanical Properties**

It has been demonstrated by earlier researchers (Kulkarni et al., 2010; Patel et al., 2012) that various geomechanical properties of the soil mass viz., undrained shear strength, compression index, void ratio, elastic modulus and Poisson’s ratio, can be determined in a noninvasive and nondestructive manner, easily, by correlating them to shear and compression wave velocities, $V_s$ and $V_p$. Conventionally, resonant column, cyclic triaxial and torsional shear tests, which are quite intricate and expensive setups, have been employed for this purpose. However, *piezo-ceramics* (bender and extender elements) have been found to be very efficient in transmitting and receiving shear and compression waves (Bartake and Singh, 2007; Bartake et al., 2008) without impacting the sample, as strains produced are <0.001%.

With this in view, a *Piezo-ceramics* were developed from the Lead Zirconate Titanate (LZT) based material, which exhibits high dielectric constant (Bhat et al., 2007), with high piezoelectric sensitivity, for low power consumption. Depending upon the requirements, these elements can be polarized in the same or opposite directions, as depicted in Fig. 22.

![Fig. 22. Different configurations of piezo-ceramics: benders (a) opposite-series and (b) same-parallel, and extenders (c) same-series and (d) opposite-parallel](image-url)
The block diagram depicted in Fig. 23 was developed for transmitting (T) and receiving (R) waves and proper functioning of the piezo-ceramics was confirmed by hearing a ‘sing’ sound when excited with a sine-wave pulse from the function generator (Bartake et al., 2008; Patel and Singh, 2009; Patel et al. 2009).

![Block Diagram](image)

Fig. 23. The arrangement for transmitting and receiving waves in the sample

In order to check the versatility of these piezo-ceramics, $V_s$ and $V_p$ were measured on standard materials and also in asphaltic concrete and very soft clays (Patel et al., 2011). $V_s$ and $V_p$ were also measured for different types of soils in their remolded and undisturbed samples, UDS, by employing the setups depicted in Fig. 24.

![Test Setups](image)

Fig. 24. The test setups used for (a) remolded and (b) undisturbed samples
The above-mentioned discussion highlights that piezo-ceramics have already been utilized to characterize fine-grained and granular geomaterials. However, this technique should be employed to detect and monitor various micro-mechanisms viz., mineralogical alteration, decomposition and fabric alteration, that prevail in the geomaterials (in their saturated, unsaturated, contaminated and multi-phase) when they interact with contaminants. In this direction, it would also be quite prudent if electrical properties (resistivity and dielectric dispersion) of the geomaterials could also be linked with the $V_s$ and $V_p$.

5. Monitoring and Simulation of Contaminant Transport

The contaminant-geomaterial interaction would also result in transport of contaminants in the soil and rock matrix. However, this interaction would be guided by, primarily, (a) the type and condition of the rock mass (intact or fractured) and (b) the soil mass (saturated or unsaturated). The fractured rock mass and the saturated soils create an easy pathway for the groundwater movement and thereby enhancing the probability of contamination of the geoenvironment (Gurumoorthy and Singh, 2004a,b; Singh et al. 2014, 2015, 2016). To counter this scenario, many a times, immobilizing agents (Arnpalli et al., 2010), tested for their sorption and desorption characteristics are employed (Pathak et al., 2014b, 2016a,b; Moghal et al., 2017). Usually, batch tests are conducted to achieve this, but due to high liquid to solid ratios, these tests fail to simulate real-life situations. Also, these tests fail to come up with recommendations regarding selection of the most suitable and general isotherm, which would describe sorption and desorption characteristics of geomaterials, precisely (Arnpalli et al., 2010; Pathak et al., 2014a, 2016a,b). This necessitates determination of the sorption-desorption characteristics of geomaterials by conducting ‘column tests’. However, due to extremely low hydraulic conductivity of the geomaterials, column tests would require large durations to yield results and hence geotechnical centrifuge modeling has been conducted (Singh and Gupta, 2000, 2001; Bartake et al., 2006).

The setup depicted in Fig. 25 was employed for determining hydraulic conductivity of the sample. This setup, when spun in a geotechnical centrifuge, simulates a conventional falling-head permeability test in an accelerated environment. The difference between the hydraulic conductivity tests and the column tests, which facilitate contaminant-geomaterial interaction, in a controlled manner, is that for
performing the later, the inner cylinder was filled with the *model contaminant*. The contaminants could be different ionic solutions in their active (radionuclides) and/or *inactive* forms. Hence, with the help of the setup depicted in Fig. 25, the *sorption* characteristics of the contaminant on geomaterial could be established. Subsequently, when the contaminant in the inner cylinder is replaced by the distilled water, the *desorption* characteristics of the contaminant-geomaterial interaction could be simulated and monitored.

![Diagram](image)

**Fig. 25. The setup employed for conducting column tests**

Subsequently, the experimental results can be employed in STANMOD ([https://www.ars.usda.gov/pacific-west-area/riverside-ca/us-salinity-laboratory/docs/stanmod-model/](https://www.ars.usda.gov/pacific-west-area/riverside-ca/us-salinity-laboratory/docs/stanmod-model/)), to establish the break-through curves, BTCs, which represent the variation of normalized concentration of the contaminant in the fresh water with respect to time, which quantify contaminant-geomaterial interaction for a given contaminant and the geomaterial. In Fig. 26a, IC-1, IC-2 and IC-3, correspond to 8 mm, 10 mm and 14.5 mm thick Israeli chalk sample, centrifuged at 125-g, 100-g and 69-g, respectively. It can be noted from the Fig. 26a that for these samples, \( C_t/C_0 \) (where \( C_0 \) is the initial concentration of the contaminant and \( C_t \) corresponds to the concentration of the effluent after time, \( t \)) attains almost unity after 62 h, 67 h and 88 h of centrifugation time, respectively. This time, denoted as \( t_{eq} \), corresponds to the
dynamic equilibrium sorption state of the material. Furthermore, it can be observed from Fig. 26(a), that initial BTCs get exhibited only after 3 h, 5 h, and 12 h of centrifugation for samples IC-1, IC-2 and IC-3, respectively. This indicates that the time, $t_i$, required for initial breakthrough to occur depends, apart from the retardation coefficient of the sample (material), on its length, $L$, and acceleration level, $N$. Further, in order to obtain $t_i$ for 1 m thick rock mass, under normal conditions (i.e., $N$=1), the concept of modeling of models was employed. The intercept of $t_i$-$N$ trend, depicted in Fig. 26(b), on the ordinate ($N$=1) is found to yield $t_i$=236113 h (i.e., 27 years). This demonstrates the utility of the geotechnical centrifuge (also known as accelerated physical modeling) modeling, for simulating and modeling sorption-desorption mechanisms, in an extremely short duration.

From this study, it has been demonstrated that the scale factors for the sorption and desorption times are 1.0 and 0.5, respectively. It is believed that the sorption and desorption parameters, obtained from the centrifuge modeling can be employed for evaluating the efficiency and suitability of immobilizing agents, and suitability of the geological formations (repositories), where the toxic/radioactive waste should be disposed.

In order to determine the presence and concentration of contaminants in geomaterials, a contaminant detector (refer Plate 1) has been developed by Rajeev and Singh (2004) and Kumar and Singh (2005). This detector helps in assessing the movement of contaminant front in a soil column (refer Plate 2). The movement of the contaminant front is done by sending a low-frequency sinusoidal signal into the sample, which is
connected to one arm of a Wheatstone's bridge. Hence, with the help of the contaminant detector, concentration of the contaminant at different locations (where electrode pairs are placed, diametrically opposite to each other) along the length of the sample can be detected (Kumar and Singh, 2005; Kumar and Singh, 2012).

Furthermore, to study the mechanism(s) of contaminant transport in the rock mass viz., diffusion and/or advection, investigations were conducted by Gurumoorthy and Singh (2004a,b,2005) and Witthüser et al. (2006) by using different ions in their active(radio nucleides) and inactive forms. Diffusion cells, depicted in Fig. 27(a)and (b) were developed for monitoring and establishing the response of the intact and fractured rock samples, respectively. Incidentally, Rao and Singh (2008) modified the diffusion cell depicted in Fig. 27(a) to accelerate the contaminant-geomaterial interaction that results in diffusive contaminant transport. This diffusion cell, refer Fig. 28, enhances the ionic diffusion through the rock sample by applying a suitable electric field across it.
Fig. 27. The diffusion cell for the (a) intact rock sample and (b) fractured rock sample

Legend: 1: Sink reservoir (millipore-water)
2: Source reservoir (water with contaminants)

Fig. 28. The diffusion cell for accelerated tests on intact rock samples
Furthermore, Sreedeep and Singh (2008) fabricated a diffusion cell (refer Fig. 29, for investigating the contaminant-geomaterial interaction when diffusive contaminant transport occurs in unsaturated soils. The BTCs have been obtained by conducting the impedance spectroscopy, IS (Rao et al., 2007a,b). This non-destructive and non-invasive technique has been found to be an excellent way of studying contaminant transport in unsaturated soils.

However, for establishing diffusion characteristics of the saturated and unsaturated soil mass, Rakesh et al. (2009) have employed the diffusion cell, depicted in Fig. 30, with sampling ports placed at regular distance on the surface of the cells. These simple studies, which employ indigenously developed diffusion cells, are found to be quite handy for preparing guidelines for safe disposal of the radioactive waste in the geoenvironment.

Fig. 29. The diffusion cell developed by Sreedeep and Singh (2008)  
Fig. 30. The diffusion cell developed by Rakesh et al. (2009)

6. Monitoring and Simulation of Heat Migration

As discussed earlier, contaminant-geomaterial interaction might also result in generation of heat, mainly due to the chemical reactions. A good example of such a situation is the MSW in landfills, wherein several chemical reactions keep occurring. Furthermore, situations like waste from nuclear and thermal power plants, underground crude oil storage tank, oil-carrying pipelines, air conditioning ducts, buried conduits and electrical cables, geothermal energy piles, furnaces, boiler units, forging units, brick kilns, solar pond and rocket launching pads (Mondal et al., 2018a), necessitate understanding the influence of heat energy on geomaterials (Yun and
Santamarina, 2008). Moreover, remediation of the contaminated land and the thermal stabilization of the soil mass and sludge sediments, underground explosions and natural freeze-thaw cycle persistently subject the migration of thermal energy in geomaterials (the soil and rock mass). Incidentally, the activities like agriculture, wherein the yield can be accelerated by employing a set of parallel buried pipes as a heating system, also induce heating of the soil mass. In all these situations, it becomes mandatory to measure the rate and extent of heat migration in the soil mass. This can be obtained by establishing the thermal regime i.e., the temperature and heat flux profiles for a prolonged duration, with the help of sensors viz., single needle probe, dual probe heat pulse (DPHP) and flux sensors (Palaparthy et al., 2013, 2017). The knowledge of thermal response of geomaterials also has a major role to play in safe and appropriate design of the underground and thermo-active structures (Abuel-Naga et al., 2015; Hytiris et al., 2017; Pellet, 2017).

In this context, efforts made by earlier researchers towards development of various techniques viz., flux plate method, calorimetric, gradient & combination, guarded hot plate, divided bar apparatus, cylindrical configuration, in-situ sphere, heat meter, thermal cell, thermal probe method (Mondal et al., 2018c), are worth appreciating. The MEMS (Micro-electro-mechanical system) based thermal sensor, differential scanning calorimeter, which are applied to sense the thermal response (say thermal properties) of the soil mass viz., thermal conductivity, resistivity, diffusivity, and volumetric heat capacity, are also being used. Though these methods and techniques are being used by the researchers and practitioners for thermal characterization of geomaterials to understand its heat migration capability, they are time-consuming, complex, tedious and costly. Also, Moreover, these methods and techniques do not imbibe the influence of microbial activities, organic content, mineralogical characteristics and heterogeneity of the geomaterials, and the MSW. It should be noted that most of these attributes of the geomaterials are sensitive to temperature and hence would have a definite influence over their thermal response, mostly at temperatures different than that prevailing at the ambiance. This calls for extensive studies to establish the mechanism of heat migration in geomaterials, by measuring their thermal response i.e., thermal regime, particularly, under variable temperature conditions. One of the ways to achieve this would be to quantify ‘the zone of influence of the heat source’, by measuring the thermal flux, $\phi$, and temperature, $\theta$, over prolonged durations in the spatial domain (Mondal et al., 2016, 2017, 2018b). This could be done...
quite efficiently with the help of flux sensors and MEMS-based temperature sensors (Susha Lekshmi et al., 2014), of extremely high precision.

As depicted in Fig. 31, the test setup for studying heat migration in soil mass consists of a mold, a hot air gun for inducing heat to the sample and a thermocol box. The hot air gun used in this study was manufactured by STEINEL thermo-power, Germany (model HL 2010 E) and it operates from 50 °C to 600 °C. The sample was prepared in a mold of dimension 150 mm×150 mm×200 mm. The four sides of the mold were made of 8 mm thick perspex and the base was made of a 10 mm thick aluminium plate. The top face of the mold (refer Fig. 31) was kept open to facilitate the flow of heat flux into the sample. After achieving a certain height of the sample, a flux sensors were embedded. It was ensured that the sensing face of these sensors faces the heat gun. A soil cover of 50 mm was ensured on the top most sensor for its proper functioning. Similarly, beneath the bottom-most flux sensor, a 30 mm thick layer of soil was maintained, which ensures 1-Dimensional heat flow in the system (refer section ABHG in Fig. 32). Subsequently, four thermocouples (T-type), were embedded in the sample to measure the temperature at the locations where heat flux sensors were installed. The response of the soil mass, corresponding to hot air gun temperature, $\theta_{hg}$, 80 °C is depicted in Fig. 33.
Apart from this, simple numerical approach, based on the finite difference method, has also been developed to solve the one-dimensional heat conduction equation, which facilitates establishment of the thermal regime in the soil mass. Also, a unified mathematical framework, AETHERES, has also been developed to estimate thermal regime in the dry soil mass. The proposed approach couples Taylor’s series into the governing differential equation of one-dimensional heat conduction (Mondal et al., 2017).

As described earlier, geomaterial-contaminant interaction might result in endo- or exothermic reactions and/or a coupled flow viz., heat-induced moisture and contaminant migration (Poulose et al., 2000; Krishnaiah and Singh, 2003b; Bao et al., 2016). For conducting such experiments, thermal probes (refer Plate 3a,b) and a thermal property detector, TPD, (refer Plate 3c) were developed (Singh et al., 2003; Dalinaidu and Singh, 2004a,b). These probes and the TPD have been found to be very helpful in determining the thermal response viz., thermal resistivity, thermal diffusivity and effusivity, and specific heat, of different geomaterials, corresponding to different moisture contents and dry densities (Gangadhara Rao et al., 1998, 1999; Singh and Gangadhara Rao, 1998; Singh and Devid, 2000; Singh et al., 2001a; Dalinaidu and Singh, 2004a,b; Sreedep et al., 2005; Krishnaiah and Singh, 2003a,2004a,2006a). Krishnaiah et al. (2004) and Das et al. (2008a,b) have employed these instruments for determining the porosity of the rock-and concrete-samples, respectively, very successfully.
Plate 3. The (a) laboratory and (b) field thermal probes and (c) thermal property detector

Incidentally, heat migration in soil mass was simulated and monitored, in a geotechnical centrifuge, (refer Plate 4) by Manthena and Singh (2001) and Krishnaiah and Singh (2004b, 2006b), the validity of ‘modeling of models’ for heat migration in soils has been demonstrated, successfully. This study also demonstrated that the geotechnical centrifuge, can be used as a research tool to model heat migration in geomaterials.

Plate 4. Instrumentation for heat migration in soils (centrifuge tests)

These studies are a good testimonial of the fact that cost-effective and indigenously made, simple looking devices viz., thermal probes and TPD, can be utilized for determining thermal properties of geomaterials such as thermal resistivity, thermal
diffusivity and specific heat, which are must to determine for proper design and safe execution of the projects mentioned above. Such in-house developments, also facilitate in demonstrating the facts; (a) thermal resistivity of geomaterials decreases as their dry-density and the moisture content increase, (b) the fine-grained soils exhibit higher thermal resistivity as compared to their counterparts, the coarse-grained soils, (c) thermal diffusivity of the geomaterials is found to be practically independent of their dry-density, (d) thermal diffusivity of the coarse-grained soils, which is maximum corresponding to the optimum moisture content, is higher than the fine-grained soils, for which the influence of the molding moisture content is practically negligible.

However, these developments should be employed, and if required augmented, for their applications to investigate (a) thermal response of multi-phase geomaterials viz., frozen geomaterials, gas hydrates and MSW, and (b) coupled phenomenon, wherein the moisture migration occurs due to the imposed thermal gradients.

7. Role of Environmental Stresses: Genesis of Unsaturated Geomaterials

Depending upon the severity of the environmental stresses, geomaterials might experience moisture loss, movement, and/or redistribution within. These mechanisms are responsible for geomaterials to acquire unsaturated-/partially-/variably-saturated state. This state of geomaterials is, primarily, dictated by the suction present in them. The variation of suction with the water content is commonly known as the soil-water characteristic/retention curve, SWCC/SWRC. A tensiometer, as depicted in Fig. 34, can be employed for soil suction measurement (Singh and Kuriyan, 2003; Sreedeep and Singh, 2005a,b). However, to overcome the limitations associated with the tensiometer measurements, which are limited to ≈100 kPa, Thakur and Singh (2005) and Thakur et al. (2005,2006) have developed a methodology, which facilitates measurement of suction up to a few Mega-Pascal. Subsequently, several methodologies were developed for measuring suction of the soil mass (Hanumantha and Singh, 2010b; Sreedeep and Singh, 2011; Jayanth et al., 2013; Kannan et al., 2013; Iyer et al., 2018a,b; Patent No. 297124).
Fig. 34. Details of the instrumentation for measuring soil suction by employing a tensiometer

Unsaturated properties of the soil mass such as water retention and hydraulic conductivity also control the contaminant migration in it (Singh et al., 2001b; Singh and Kuriyan, 2002, 2003). Earlier studies reveal that these characteristics mainly depend on the mineralogy, water content, dry-density and degree of saturation of the soil (Rao et al., 2011, Patent No. 277842). With this in view, various in-situ, laboratory techniques, empirical relationships and Pedo-transfer functions (PTFs), have been developed by the researchers to establish soil-water characteristic curve, SWCC, (Thakur et al., 2005, 2006, 2007; Shah et al., 2006; Sreedeep and Singh, 2006b; Jayanth et al, 2012). However, these techniques are tedious, time-consuming, soil specific, require expensive experimental setups and resort to destructive and invasive techniques for determining soil moisture content (Sreedeep and Singh, 2005b). Also, most of these techniques suffer particularly in regeneration of the in-situ soil conditions and boundary conditions, in an exceptionally small models (Borana et al., 2018). Usually, the SWCC is employed for estimating hydraulic conductivity of the unsaturated soil mass. Hence, techniques that would be helpful in (a) creating the unsaturated state of the soil mass and (b) determination of the unsaturated hydraulic conductivity of the soils, under laboratory and field conditions directly, were developed, as described below.
7.1 Laboratory Simulation of Unsaturated State of Geomaterials

The first step in this direction would be to create unsaturated state of the soil mass by (i) employing a geotechnical centrifuge, (ii) imposing thermal flux and (iii) employing a pressure membrane extractor (PME), and determining its instantaneous moisture content by conducting electrical measurements (i.e., voltage across two points in the soil mass). The utility of these techniques for establishing the SWCC, easily and that too in a nondestructive and noninvasive manner has been demonstrated (Hanumantha Rao and Singh, 2010a,b; Rao and Singh, 2012).

7.1.1 By Centrifugation

The test setup depicted in Fig. 35 was fabricated to attain an unsaturated state of the sample, by centrifugation, followed by establishing the SWCC. As depicted in the figure, point electrodes were fitted diagonally opposite to each other and the voltage across each pair of electrodes, \( V \), was measured by employing the soil conductivity meter developed by Rajeev and Singh (2004).

![Fig. 35. The setup used for creating unsaturated state of the soil mass by centrifugation](image)

The soil sample (in a slurry form) was poured into the perspex cylinder and later centrifuged for different centrifugation efforts (time and g-level, designated as \( N \)). Due to centrifugation, water drains out of the sample and it acquires the unsaturated state.
At the end of each centrifugation effort, the setup was taken out of the centrifuge and voltage, $V$, across different electrode pairs was measured. Later, a stainless steel ring was used for retrieving a specimen of the soil for measuring its suction, $\psi$, by employing a dewpoint potentiometer, WP4, (Shah et al., 2006). Subsequently, the ring containing the soil specimen was placed in an oven to determine its moisture content, $w$. Fig. 36(a) depicts the variation of the measured voltage, $V$, across electrode pairs A-A, B-B and C-C, with time, $t$. For the sake of brevity, results of $N=530$, only, are being presented. It can be observed from the trends depicted in the figure, $V$ decreases as $t$ increases, which indicates that the resistance of the soil mass increases, due to the expulsion of water as a result of enhanced centrifugation efforts. This observation further indicates that soil mass achieves certain unsaturated state after each centrifugation (Pouluse et al., 2000; Singh et al., 2001; Singh and Kuriyan, 2002).

It was also observed that the difference between the values of $V$ corresponding to a given time between two electrode pairs decreases for higher values of $N$. This indicates that centrifugation at higher $N$ creates a uniform state of moisture in the sample in a short duration of time. The results have been employed for developing the soil-water characteristic curve, $\text{SWCC}_{(\text{Cent})}$, using the Fredlund and Xing (1994) best fit. Further, to demonstrate the utility of the proposed technique, the obtained $\text{SWCC}_{(\text{Cent})}$ was compared vis-à-vis the SWCCs reported by researchers (Shah et al., 2006), $\text{SWCC}_{(\text{PME-WP4})}$, and obtained from the pedo-transfer function, PTF, proposed by Fredlund et al., (1997), $\text{SWCC}_{(\text{PTF})}$, as depicted in Fig. 36(b). A reasonably good match between the $\text{SWCC}_{(\text{Cent})}$ and $\text{SWCC}_{(\text{PME-WP4})}$ can be noticed.
7.1.2 By Imposition of Thermal Flux

The test setup depicted in Fig. 37 was fabricated, as an alternative to the setup depicted in Fig. 35, to create unsaturated samples and for establishing the SWCC. The *laboratory thermal probe* is the most important part of this setup.
The curved surface of the inner cylinder is perforated in the radial direction. Due to imposition of the thermal flux, water from the soil sample permeates through these perforations and gets collected in the outer cylinder. The electrodes that are fitted on top and bottom plates facilitate measurement of the $V$ with the help of a soil conductivity meter. Also, the cover plate has been provided with four 3 mm diameter holes for fitting thermocouples, which are placed at different radial distances from the probe. Fig. 38(a) depicts the variation of temperature, $\theta$, and measured voltage, $V$, with time, $t$, obtained by imposing a heat flux, $Q$, of 59.5 W/cm, through the thermal probe.

![Graphs showing temperature and voltage variations](image)

**Fig. 38. The variation of (a) temperature and (b) voltage across different electrodes, due to imposition of thermal flux**

It can be observed from Fig. 38(a) that $\theta$ varies with time, $t$, and the maximum temperature built up in the soil mass is about 30 to 40 °C (except for the surface of the probe on which temperature rise is up to 50 to 60 °C). It can also be noticed that, as expected, the rise in $\theta$ is least for the thermocouples located at higher radial distances, for a given $t$. Trends depicted in Fig. 38(b) indicate that in general, $V$ decreases with an increase in $t$. This phenomenon can be attributed to the increase in resistance of the soil mass, due to thermal flux induced moisture migration and hence creation of its unsaturated state. Subsequently, $w$ and $\psi$ for different values of $V$ were computed, and the results are presented in Fig. 39. This data can be employed for developing the soil-water characteristic curve due to thermal flux, $\text{SWCC}(\text{TF})$, using the Fredlund and Xing...
(1994) best fit. Further, to demonstrate utility of the proposed technique the SWCC\textsubscript{(TF)} was compared vis-à-vis the SWCCs reported by researchers (Shah et al., 2006), SWCC\textsubscript{(PME-WP4)}, and obtained from the pedo-transfer function proposed by Fredlund et al., (1997), SWCC\textsubscript{(PTF)}, as depicted in the Fig. 39. A reasonably good match between the SWCC\textsubscript{(TF)} and SWCC\textsubscript{(PME-WP4)} can be noticed from this figure.

![Fig. 39. Validation of the methodology for obtaining SWCC by imposition of thermal flux on sample](image)

7.1.3 **By Employing Pressure Membrane Extractor (PME)**

The PME unit, employed for creating different moisture states of the specimen, works in the pressure range of 0-1500 kPa and consists of a stainless steel pressure chamber and a base plate, refer Fig. 40.

![Fig. 40. The setup used for creating unsaturated state of the soil mass by employing a pressure membrane extractor](image)
Four PVC rings (60 mm internal diameter and 20 mm height) were used as specimen holders. These rings contain two pairs (1-1 and 2-2) of stainless steel point electrodes of 2 mm diameter, located diagonally opposite to each other. This arrangement helps in measuring voltage across two points, $V$, in the soil specimen. Subsequently, as explained earlier, its moisture content, $W$ was also determined. However, this technique yields the response of the soil mass only up to the applied pressure, which is equal to suction, $\psi \leq 1500$ kPa. Hence, the utility and efficiency of these three techniques for establishing the SWCC has been demonstrated. The most important feature of these techniques is that just by measuring the voltage across two points in the soil mass, its SWCC can be established, quite easily, and that too in a nondestructive and noninvasive manner. It is recommended that extensive experimentations should be conducted to generalize the suitability of the proposed technique for establishing SWCC of different types of soils.

Further, as depicted in Fig. 41, the unsaturated soil hydraulic conductivity, $k_u$, obtained by employing these three techniques and the PTFs, available in the SoilVision database®, were compared. It must be appreciated that $k_u(N)$ are directly measured values, by adopting the methodology proposed by Singh and Kuriyan (2003), and not mathematically predicted. It’s interesting to note that for all practical purposes, $k_u(N)$ of the soil mass does not depend on $N$.

![Fig. 41. Evaluation of different techniques employed for estimating unsaturated soil hydraulic conductivity](image-url)
Hence, it can be said that these methodologies are very useful and handy for establishing the soil-water characteristic curve and for estimating the hydraulic conductivity of unsaturated soils, either directly (in case of centrifugation) or indirectly (i.e. by employing pedo-transfer functions, PTFs).

7.2. In-situ Lysimeter

Laboratory column studies (under normal and accelerated gravity environments), numerical modeling and pedo-transfer functions (Thakur et al., 2007) have been employed by the researchers to determine hydraulic conductivity of unsaturated soils (Singh and Kuriyan, 2003; Hanumantha Rao et al., 2009) and studying contaminant transport (Rao et al., 2011) in them. However, these methods suffer from several limitations, particularly, as far as regeneration of in-situ soil conditions and boundary conditions, in an exceptionally small model, are concerned. Under these circumstances, an in-situ lysimeter (Fig. 42, legends used in the figure are explained in the table) has been found to be quite useful for conducting the investigations to obtain hydraulic conductivity of fully- or partially-saturated soils (Hanumantha Rao et al., 2009; Rao et al., 2011). A tubular TDR probe, has been employed for determining the volumetric moisture content, \( \theta \), of the soil as a function of depth, \( z \), by inserting it into access tubes T1 and T2.

![Fig. 42. Details of the in-situ lysimeter](image-url)
Fig. 43 depicts spatial variation in the volumetric moisture content, \( \theta \), of the soil mass corresponding to different monsoon seasons (full-monsoon, medium-dry and dry seasons). Trends depicted in the Fig. 43 (a) show that \( \theta \) varies over a wide range from 5\% during the fully-dry season to 45\%, during the full-monsoon season, which correspond to retention and saturation capacity of the soil mass, respectively. It can also be noticed from the Fig. 43 (a) that \( \theta \) increases with depth \( z \). However, a significant scatter in \( \theta \) values can be observed for \( z < 300 \) mm, only. Further, since unsaturated soil hydraulic conductivity, \( k_u \), is a function of suction, \( \psi \), efforts were made to determine suction of the soil mass in the lysimeter \( \psi_f \) by employing SWCC, with the help of Fredlund and Xing (1994) fitting function, to the corresponding measured \( \theta \) values, as depicted in Fig. 43(b). Hence, by knowing \( \psi_f \), \( k_u \) was computed by using the PTF proposed by Fredlund et al. (1994), as depicted in Fig. 43(c).

Fig. 43. The variation of (a) volumetric moisture content, (b) suction, and (c) \( k_u \), with \( z \) for different monsoon seasons

8. Role of Environmental Stresses: Cracking of Fine-grained Soils

The cracking of fine-grained soils, can be attributed to the loss of moisture, as a result of its exposure to severe environmental stresses, as discussed above. These conditions might cause a non-uniform distribution of moisture and temperature, which might result in an imbalance of the internal energy. The loss of moisture from the fine-
grained soils results in their shrinking and subsequently cracking, if they are restrained from undergoing volumetric changes, termed as shrinkage. It has been observed that cracking of the fine-grained soils influences its overall engineering behavior (in particular the hydraulic conductivity, consolidation, compressibility and shear strength characteristics). Hence, it becomes mandatory to investigate the mechanism(s) of soil cracking and the parameters that influence it significantly.

In this context, several experimental techniques viz., triaxial tests, direct tensile tests or suction measurements, have been developed and employed by earlier researchers to measure the tensile strength of fine-grained soils (Venkataramana et al., 2009) and to study their cracking characteristics (Uday and Singh, 2013a,b; Patent No. 277862). However, these studies yield results that are soil specific and dependent on the methodology adopted. Apart from this, due to the bulk form of the sample, the sample heterogeneity (i.e., both in terms of the density and the moisture content) influences test results to a great extent. Under this situation, and in the absence of guidelines regarding sample thickness, determination of the tensile strength of expansive clays by employing their thin samples (1 mm to 5 mm) appears to be an excellent alternative. Efforts have been made to determine tensile strength of fine-grained soils, by resorting to techniques that deal with measurement of the (a) deflection undergone by a silicon wafer, (refer Fig. 44a and b), due to air-drying of a thin film of these clays, with the help of a laser beam (Shinde et al., 2012), and (b) measuring suction by employing a dewpoint potentiometer, WP4 (Thakur et al., 2006). Results obtained from these techniques were critically evaluated vis-à-vis those obtained from triaxial tests and empirical relationships available in the literature. It has been observed that there is a unique relationship between the results of the thin and thick samples and hence thin samples of expansive clays can be employed for determining their tensile strength (Tej and Singh, 2013; Uday et al., 2014,2015). This shows the usefulness of the proposed techniques for measuring the tensile strength of the fine-grained, that too expansive soils (Bharat et al., 2013; Jha and Sivapullaiah, 2017).

The photograph and the schematic of the experimental set up used to measure the tensile stress developed in the thin film are depicted in Fig. 44(a) and (b), respectively. As depicted in Fig. 44(b), L1 and L2 are incident and reflected rays, respectively, and X is the displacement of the laser beam on the detector due to certain deflection of the wafer.
Subsequently, \( X \), and stress, \( \sigma \), as a function of time are recorded for thin film, as depicted in Fig. 45. The stress corresponding to the peak value yields the tensile strength of the specimen.

This methodology of determining tensile strength of fine-grained soils, in tandem with application of dewpoint potentiometer, WP4, for expansive soils, in particular, corresponding to different liquid to solid ratios has been found to be quite useful. Results obtained from these methodologies were critically evaluated vis-à-vis those obtained from the triaxial tests and the empirical relationships reported in the literature. It has been observed that there is a unique relationship between the results
of the thin and thick samples. Hence, the proposed methodology can be employed for determining tensile strength of the fine-grained soils, just by knowing their mineralogical composition and the water content. However, extensive studies should be conducted on different minerals, and soils of different mineralogical composition to generalize these findings.

9. Concluding remarks&the Path Ahead

Various instrumentation techniques developed by THE ENVGEOS for providing solutions to various geoenvironmental issues have been presented in this paper. These techniques facilitate obtaining appropriate solutions to storage and safe disposal of hazardous and toxic wastes in geomaterials and thus minimizing the adverse effect on the geoenvironment. Though most of these techniques are found to be functioning quite satisfactorily in the laboratory environment, extensive in-situ investigations must be carried out that too on different types of geomaterials to demonstrate their robustness and suitability.

Though the (limited) contents of this paper must have successfully highlighted the necessity of interdisciplinary research in the field of contemporary geotechnical engineering, the following needs are to be addressed:

1. The impact of biogeochemical (bio-mediated) processes viz., decay, degradation and upgradation, that occur in geoenvironment, on geomaterials, should be studied and included in the analysis of geotechnical problems. The modification of engineering characteristics of the coarse-grained soils due to biologically induced mineralization is an excellent example, in this context.

2. The role of geomaterial and pore-fluid interaction in the soil matrix at the micro-structure level to address the real-life situations such as offshore landslides, sedimentation, migration of the fines and slurry transportation for various industrial applications viz., dredging and mineral processing, should be studied. In order to address this, investigations are warranted on the rheological behavior of soil-water systems corresponding to water content higher than the liquid limit (Shetty et al., 2018).
3. Accelerated decomposition of (a) unsegregated municipal solid waste, MSW, in a bioreactor landfill and (b) organic content rich soils, should be studied extensively, in line with the philosophy, waste to energy. Also, pilot-scale studies to incorporate the effect of heterogeneity on various physico-biochemical properties associated with these geomaterials, with the help of sensors and probes, should also be attempted. Apart from the laboratory and field investigations, numerical modeling related to coupled processes that are responsible for decomposition of these geomaterials must be attempted (Reddy et al., 2017b). Attempts should also be made to utilize the non-degradable fraction of the residues, which is a source of refuse-derived fuel, RDF, from the MSW.

4. The MSW landfill mining, a precursor to their Rehabilitation and reclamation of the derelict land, is shaping up as a giant ‘techno-socio-economical’ issue, which should be handled with great diligence. However, it should be realized that the landfill mining would result in extreme volumes of the landfill mined residues and subsequently their handling, segregation, storage, transportation and utilization for development of infrastructure and soil conditioning needs to be addressed scientifically. Appropriate standards, guidelines and policies need to be developed in this context.

5. The industrial by-products, IBPs, viz., bauxite residues, slags, fly ash, mine overburden dumps, tailings, plastics, etc., should be treated as the man-made resource for sustainable development (Mohamed, 2015; Reddy et al., 2018). This could be attained by developing proper technology(ies) based on extensive R&D for bulk utilization of the IBPs. Attempts should also be made towards the creation and implementation of appropriate policies. In this context, the hazard and toxicity zonation of the entire country would be advantageous.

6. Geomechanical modeling of multi-phase geomaterials viz., permafrost, gas hydrates bearing sediments, thermally stabilized soils, the municipal solid waste, etc., which is still in its nascent stage, should be taken up.

However, in order to accomplish such contemporary research, indigenous development of the test setups and paraphernalia, which also falls in line with the Government of India initiative, MAKE IN INDIA, is the dire need of the hour. Furthermore, most of these issues could easily be taken up as startups by the
professionals, who are concerned about the generations to follow, and for whom the sky is the limit. This would also remind them that the path ahead is not so easy to tread but if they desire to blossom like a rose in the garden, they have to learn the art of adjusting with the thorns.

I would also like to add here that audiences’ critical comments and suggestions are utmost welcome without which it would be difficult for The ENVGEOS to march ahead and follow the philosophy Never stop learning, because life never stops Teaching .... Furthermore, the outcome of these initiatives should be adopted, challenged and improvised in view of the fact that Life is a Camera, Focus on what’s important Capture the good times, Develop from the negatives and if things don’t work out, Take another Shot...

Acknowledgments

I would like to sincerely thank the Indian Geotechnical Society for selecting me to deliver the 40th IGS Annual Lecture, which has provided me an opportunity to introspected my activities, in the extremely intriguing and enchanting field of GEOENVIRONMENTAL ENGINEERING(Singh, 2016). It was indeed a privilege to receive feedback on the philosophy of developing this manuscript from my Gurus (Prof. P. K. Basudhar, Prof. Yudhbir, Prof. C. S. Desai, Prof. M. R. Madhav, Prof. N. S. V. Kameswara Rao and Prof. S. Chandra). This interaction, certainly reminded me of the days that I spent at IIT Kanpur as a student and research scholar. As many who had been associated with me have echoed, without the unconditional support and motivation that I have received from Mrs. Ritu Singh, my better-half, and Ms. Yashi Singh, my daughter, is beyond describing in words.

Help received from Dr. Anjan Patel, Prof. Ashok Kr. Gupta, Dr. Nevin Koshy, Dr. Prabir Kolay and Dr. Vikas Sharma in the entire course of preparation of this manuscript is thankfully acknowledged. My research group (Shashank, Rakshith, Ganaraj, Arif, Chandana, Lijith, Bhini, Goli Venkata, Himanshu and Tushar) deserves a special thankyoufor motivating and assisting me in developing this manuscript. I take this opportunity to acknowledge the help and support that I have received from the examiners of theses, (invisible) reviewers and editorial board members of various Journals, which turned out to be a blessing in disguise for THE ENVGEOS. The financial help from various funding agencies and industries is also thankfully acknowledged.
References
1. Abuel-Naga, H., Raouf, M.I.N., Raouf, A.M.I. and Nasser, A.G., “Energy Piles: Current State of Knowledge and Design Challenges”, Environmental Geotechnics, 2015, 2(4), 195-210.

2. Abu-Zreig, M.M., Al-Akhras, N.M. and Attom, M.F., “Influence of Heat Treatment on the Behavior of Clayey Soils”, Applied Clay Science, 2001, 20, 129-135.

3. Akbulut, S. and Arasan, S., “The Variations of Cation Exchange Capacity, pH, and Zeta Potential in Expansive Soils Treated by Additives”, International Journal of Civil and Structural Engineering, 2010, 1(2), 139-154.

4. Arnepalli, D.N., Rao, B.H., Shanthakumar, S. and Singh, D.N., “Determination of distribution coefficient of geomaterials and immobilizing agents”, Canadian Geotechnical Journal, 2010, 47, 1139-1148.

5. Arnepalli, D.N., Shanthakumar, S., Rao, H.B. and Singh, D.N., “Comparison of Methods for Determining Specific Surface Area of Fine-grained Soils”, Geotechnical and Geological Engineering, 2008, 26(2), 121-137.

6. Arulrajah, A., “The Importance of Environmental Geotechnics”, Environmental Geotechnics, 2015, 1(4), 197.

7. ASTM C 204 (1984). “Standard Test Method for Fineness of Portland Cement by Air Permeability Apparatus”, Annual Book of ASTM Standards, 04.01, ASTM, West Conshohocken, PA, USA, 56-162.

8. ASTM D 4646-03 (2008). “Standard test method for 24-h Batch-Type measurement of contaminant sorption by soils and sediments”, ASTM International, West Conshohocken, Pennsylvania 19428-2959, US.

9. Azizian, S., “Kinetic Models of Sorption: A Theoretical Analysis”, Journal of Colloid and Interface Science, 2004, 276, 47-52.

10. Bao, J., Xu, Z. and Fang, Y., “A Coupled Thermal-hydro-mechanical Simulation for Carbon Dioxide Sequestration”, Environmental Geotechnics, 2016, 3(5), 312-324.

11. Bartake, P.P. and Singh, D.N., “A Generalized Methodology for Determination of Crushing Strength of Granular Materials”, Geotechnical and Geological Engineering, 2007, 25, 203-213.

12. Bartake, P.P. and Singh, D.N., “Determination of Crushing Strength of Cenospheres”, Journal of ASTM International. 2005, 2(7), DOI: 10.1520/JAI13092.

13. Bartake, P.P. and Singh, D.N., “Studies on Determination of Shear Wave Velocity in Sands”, Geomechanics and Geoengineering: An International Journal, 2007, 2(1), 41-49.

14. Bartake, P.P., Patel, A. and Singh, D.N., “Instrumentation for Bender Element Testing of Soils”, International Journal of Geotechnical Engineering, 2008, 2(4). 395-405.
15. Bartake, P.P., Raghunandan, S. and Singh, D.N., “Modelling Liquefaction of Sand in a Geotechnical Centrifuge”, Jr. of South East Asia Geotechnical Society, 2006, 131-135.

16. Bathija, A.P., Liang, H., Lu, N., Prasad, M. and Batzle, M. L., “Stressed Swelling clay”, Geophysics, 2009, 74(4), A47-A52.

17. Bayat, H., Ebrahimi, E., Ersahin, S., Hepper, E.N., Singh, D.N., Amer, A.M.M. and Yukselen-Aksoy, Y., “Analyzing the Effect of Various Soil Properties on the Estimation of Soil Specific Surface Area by Different Methods”, Applied Clay Science, 2015, 116-117. 129 - 140.

18. Benson, C. H., “The Future of Environmental Geotechnics: Creating the New Value Proposition”, Environmental Geotechnics, 2016, 3(2), 61-62.

19. Bharat, T.V., Sivapullaiah, P.V. and Allam, M.M., “Novel Procedure for the Estimation of Swelling Pressures on Compacted Bentonites based on Diffuse Double Layer Theory”, Environmental Earth Sciences, 2013, 70(1), 303-314.

20. Bhat, A.M., Rao, B.H., and Singh, D.N., “A Generalized Relationship for Estimating Dielectric Constant of Soils”, Journal of ASTM International, 2007, DOI: 10.1520/JAI100635.

21. Bo, M. W., “The Role of Environmental Geotechnics”, Environmental Geotechnics, 2015, 1(4), 198.

22. Borana, L., Yin., Jian-Hua., Singh, D.N., Shukla, S.K. and Tong, F., “Direct Shear Testing Study of the Interface Behavior between Steel Plate and Compacted Completely Decomposed Granite under Different Vertical Stresses and Suctions”, Journal of Engineering Mechanics, ASCE, 2018, 144(1), 04017148.

23. Brooks, R. H. and Corey, A. T., “Hydraulic Properties of Porous Medium”, Hydrology paper, 1964, Colorado State University, Fort Collins, Colorado.

24. Chembukavu, A.C., Mohammad, A. and Singh, D.N., “Bioreactor Landfills in Developing Countries: A Critical Review”, The Journal of Solid Waste Technology and Management, 2019 (In print).

25. Chorom, M. and Rengasamy, P., “Effect of Heating on Swelling and Dispersion of Different Cationic forms of a Smeectite”, Clay and Clay Minerals, 1996, 44(6), 783-790.

26. Cox, R.J., Peterson, H.L., Young, J., Cusik, C. and Espinoza, E.O., “The Forensic Analysis of Soil Organic by FTIR”, Forensic science International, 2000, 108, 107-116.

27. Dalinaidu, A. and Singh, D.N., “A Field Probe for Measuring Thermal Resistivity of Soils”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE. 2004,130(2), 213-216.

28. Dalinaidu, A. and Singh, D.N., “A Generalized Procedure for Determining Thermal Resistivity of Soils,” International Journal of Thermal Sciences. 2004, 43(1), 43-51.
29. Dalinaidu, A., Das, B.B. and Singh, D.N., “Methodology for Rapid Determination of Pozzolanic Activity of Materials”, Journal of ASTM International, 2007, DOI: 10.1520/JAI100343.

30. Dangayach, S., Singh, D.N., Kumar, P., Dewri, S.K., Roy, B., Tandi, C. and Singh, J., “Thermal Instability of Gas Hydrate Bearing Sediments: Some Issues”, Marine and Petroleum Geology. 2015, 67, 653-662.

31. Daphalapurkar, N.P., Wang, F., Fu, B., Lu, H. and Komanduri R., “Determination of Mechanical Properties of Sand Grains by Nanoindentation”, Experimental Mechanics, 2011, 51(5), 719-728.

32. Das, B.B., Singh, D.N. and Pandey, S.P., "Experimental Revalidation of Certain Durability Design Provisions for Concrete with Reference to the Indian Code of Practice", Cement Wapno Beton, 2008b, XIII/LXXV(1). 9-18.

33. Das, B.B., Singh, D.N. and Pandey, S.P., "Rapid Chloride Ion Permeability of OPC and PPC based Carbonated Concrete", Journal of Materials in Civil Engineering, ASCE, 2011, 24(5), 606–611.

34. Das, B.B., Singh, D.N. and Pandey, S.P., “Some Investigations for Establishing Suitability of Watson's Strength-porosity Model for Concrete”, Journal of ASTM International, Published Online: 02 January 2008a, DOI: 10.1520/JAI101345.

35. Du, Y.J., Ning-Jun, J., Liu, S., Jin, F., Singh, D.N. and Puppala, A. “Engineering Properties and Microstructural Characteristics of Cement Stabilized Zinc-Contaminated Kaolin”, Canadian Geotechnical Journal, 2014, 51, 289–302.

36. Du, Y.J., Ning-Jun, J., Liu, S., Jin, F. and Singh, D.N., “Physical Properties, Electrical Resistivity and Strength Characteristics of Carbonated Silty Soil Admixed with Reactive Magnesia”, Canadian Geotechnical Journal. 2015, 52(11). 1699-1713.

37. Eisazadeh, A., Kassim, K.A. and Nur, H., “Solid-state NMR and FTIR Studies of Lime Stabilized Montmorillonitic and Lateritic Clays”, Applied Clay Science, 2012, 67(68), 5-10.

38. ESP, “Electrostatic precipitator manual”, The Mcilvaine Company, Northbrook, Illinois, USA. 1976.

39. Fan, R.D., Liu, S.Y., Du, Y.J., Reddy, K.R. and Yang, Y.L., “Impacts of Presence of Lead Contamination on Settling Behavior and Microstructure of Clayey Soil.” Applied Clay Science, 2017, 142, 109-119.

40. Fredlund, D.G. and Xing, A., “Equations for the Soil Water Characteristic Curve”, Canadian Geotechnical Journal, 1994, 31, 533-546.

41. Fredlund, D.G., Fredlund, M. G. and Wilson, G. W., “Estimation of Unsaturated Soil Properties using a Knowledge-based System”, Proc. of the 2nd Int. Conf. on unsaturated soils, UNSAT’98 Beijing, China, 1998, 17-30,
42. Fredlund, D.G., Fredlund, M. G. and Wilson, G. W., “Prediction of the Soil-Water Characteristic Curve from Grain-size Distribution and Volume-mass Properties”, 3rd Brazilian symposium on unsaturated soils, Rio de Janeiro, Brazil, 1997, 1-12.

43. Fredlund, D.G., Xing, A. and Huang, S., “Predicting the Permeability Function for Unsaturated Soil using the Soil-water Characteristic Curve,” Canadian Geotechnical Journal, 1994, 31(3), 533-546.

44. Ganaraj, K. and Singh, D.N., “Contemporary Issues Related to Utilization of Industrial Byproducts”. Advances in Civil Engineering Materials. ASTM International, 2017, 6(1), 444-479.

45. Gangadhara Rao, M.V.B.B. and Singh, D.N., "A generalized Relationship to Estimate Thermal Resistivity of Soils", Canadian Geotechnical Journal, 1999, 36(4), 767-773.

46. Gangadhara Rao, M.V.B.B., Kolay, P.K. and Singh, D.N., "Thermal Characteristics of a Class F Fly ash", Cement and Concrete Research, 1998, 28(6), 841-846.

47. Goreham, V.C. and Lake, C.B., “Diffusion and Sorption of Volatile Organic Compounds through Soil-cement Materials”, Environmental Geotechnics, 2018, 5(3), 134-145.

48. Gumaste, D.S. and Singh, D.N., “Laboratory Studies to Investigate the Influence of Thermal Energy on Soil-fabric”, Geomechanics and Geoengineering: An International Journal, 2013, 8(3), 209-214.

49. Gumaste, S.D. and Singh, D.N., "Application of Impedance Spectroscopy for Determining Fabric Anisotropy of Fine-grained Soils" Journal of Testing and Evaluation, ASTM, 2010. 38(3), 309-318.

50. Gumaste, S.D., Iyer, K.R., Sharma, S., Channabasavaraj, W., and Singh, D.N. “Simulation of Fabric in Sedimented Clays”, Applied Clay Sciences, 2014, 91-92, 117-126.

51. Gumaste, S.D., Iyer, K.R., Sharma, S., Singh, D.N., “Determination of the fabric alteration of marine clays”, Acta Geotechnica Slovenica, 2014b, 11(2), 21-31.

52. Gurumoorthy, C. and Singh, D.N., “Centrifuge Modeling of Diffusion Through the Rock Mass,” Journal of Testing and Evaluation, ASTM. 2005, 31(1), 562-568.

53. Gurumoorthy, C. and Singh, D.N., “Diffusion of Iodide, Cesium and Strontium in Charnokite Rock Mass,” Journal of Radioanalytical and Nuclear Chemistry, 2004a, 262(3), 639-644.

54. Gurumoorthy, C. and Singh, D.N., “Experimental Methodology to Assess Contaminant Diffusion in Rock Mass,” Journal of Environmental Monitoring and Assessment. 2004b, 91, 277-291.

55. Hanumantha Rao, B. and Singh, D.N., “Application of Thermal Flux for Establishing Soil-Water Characteristic Curve of Kaolin”, Geomechanics and Geoengineering: An International Journal, 2010a, 5(4), 259-266.
56. Hanumantha Rao, B. and Singh, D.N., “Establishing Soil-water Characteristic Curve of a Fine-grained Soil from Electrical Measurements”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2010b, 136(5), 751-754.

57. Hanumantha Rao, B., Sridhar, V., Rakesh, R.R., Singh, D.N., Narayan, P.K. and Wattal, P.K., “Application of In-situ Lysimetric Studies for Determining Soil Hydraulic Conductivity”, Geotechnical and Geological Engineering, 2009, 27, 595-606.

58. Hanumantha Rao, B., Sridhar, V., Rakesh, R.R., Singh, D.N., Narayan, P.K. and Wattal, P.K., “Lysimetric Studies for Modelling Radioactive Contaminant Transport in Soils”, Int. J. of Environment and Waste Management, IJEWM, 2013, 12(3), 318-339.

59. Hatten, J., Zabowski, D., Scherer, G. and Dolan, E., “Comparison of Soil Properties after Contemporary Wildfire and Fire Suppression,” Forest Ecology and Management, 2005, 220(1-3), 227-241.

60. Hoyos, L.R., DeJong, J.T., McCartney, J.S., Puppala, A.J., Reddy, K.R. and Zekkos, D., “Environmental Geotechnics in the U.S. Region: A Brief Overview.”Environmental Geotechnics, 2015, 2(6), 319-325.

61. Hytiris, N., Emmanuel, R., Aaen, B., Church, E.S., Campbell, D.S., Ninikas, K. and Robertson, A., “Heat Recovery from Mineworkings: Opportunities in the Glasgow Area”, Environmental Geotechnics, 2017, 4(6), 395-401.

62. IAEA (2004) Safety assessment methodologies for near surface disposal facilities, results of a coordinated research program, Review and Enhancement of Safety Assessments Approaches and Tools, Vol. 1, International Atomic Energy Agency, Vienna.

63. Iyer, K.R., Jeevan, J., Shetty R. and Singh, D.N., “Some Investigations to Quantify Hysteresis Associated with Water Retention Behaviour of Fine-grained Soils”, Geomechanics and Geoengineering: An International Journal, 2018a, 1-12, DOI: 10.1080/17486025.2018.1445872

64. Iyer, K.R., Joseph, J., Lopes, B.C.F.L., Singh, D.N. and Tarantino, A., “Water Retention Characteristics of Swelling Clays in Different Compaction States”, Geomechanics and Geoengineering: An International Journal, 2018, 13(2), 88-103.

65. Jayanth, S., Iyer, K. and Singh, D.N., “Continuous Determination of Drying-path SWRC of Fine-grained Soils”, Geomechanics and Geoengineering: An International Journal, 2013, 8(1), 28-35.

66. Jayanth, S., Iyer, K. and Singh, D.N., “Influence of drying- and wetting- cycles on SWCCs of fine-grained soils”, Journal of Testing and Evaluation, ASTM, 2012, 40(3), 376-386.

67. Jayanthi, P.N.V., and Singh, D. N., “Utilization of Sustainable materials for Soil Stabilization: State-of-the-art”, Advances in Civil Engineering Materials. ASTM International, 2016, 5(1), 46-79.
68. Jayanthi, P.N.V., Kuntikana, G. and Singh, D. N., “Stabilization of Fine-Grained Soils Against Desiccation Cracking Using Sustainable Materials”, Advances in Civil Engineering Materials. ASTM International, 2017, 6(1), 36-66.

69. Jha, A.K. and Sivapullaiah, P.V., “Role of Gypsum on Microstructure and Strength of Soil”, Environmental Geotechnics, 2016, 3(2), 78-89.

70. Jha, A.K. and Sivapullaiah, P.V., “Volume Change Behavior of Gypseous Soil”, Journal of Materials in Civil Engineering, 2017, 29(10), Article number06017010.

71. Jha, B. and Singh, D.N., “A Review on Synthesis, Characterization and Industrial Applications of Flyash Zeolites”, Journal of Materials Education, 2011,33(1-2),65-132.

72. Jha, B. and Singh, D.N., “A Three Step Process for Purification of Fly Ash Zeolites by Hydrothermal Treatment”, Applied Clay Science, 2014c,90, 122-129.

73. Jha, B. and Singh, D.N., “Formation of Meso- and Micro-Pores in Fly Ash Zeolites by Three-step Activation”, ACTA GEOTECHNICA SLOVENICA. 2014a, 11(1), 63-69.

74. Jha, B. and Singh, D.N., “Quantification of Transitions Occurring in a Hydrothermally Activated Fly Ash”, Materials Performance and Characterization, ASTM, 2014b, 3(1), 239-254.

75. Jha, B. and Singh, D.N., “Synthesis of Higher Grade Fly Ash Zeolite X from Fly Ash by Three Step Fusion”, Materials Performance and Characterization, ASTM, 2013, 2(1), 285-295.

76. Jha, B. and Singh, D.N., “Zeolitization Characteristics of a Flyash from Wet- and Dry- Disposal Systems”, ACTA GEOTECHNICA SLOVENICA, 2012, 2, 63-71.

77. Jha, B., Koshy, N. and Singh, D.N., “Establishing two-stage Interaction between Fly ash and NaOH by X-ray and Infrared analyses”, Frontiers of Environmental Science & Engineering, 2015, 9(2), 216-221.

78. Johnston, P. M. and O’Kelly, B. C., “Importance of Environmental Geotechnics”, Environmental Geotechnics, 2016, 3(6), 356-358.

79. Joseph, J., Dangayach, S., Singh, D.N., Kumar, P., Dewri, S.K., Tandi, C. and Singh. J., “Investigation on Excess Gas Method for Synthesis of Methane Gas Hydrates”, Journal of Natural Gas Science & Engineering, 2015, 42, 203-215.

80. Joseph, J., Singh, D.N., Kumar, P., Dewri, S.K., Tandi, C. and Singh, J., “State-of-the-Art on Gas Hydrates and Relative Permeability of Hydrate Bearing Sediments”, Marine Georesources & Geotechnology, 2016, 34(5), 450-464.

81. Kadali, S., Sharma, S. and Singh, D.N., “Application of Nanoindentation to Establish Influence of Heat on Soils”, Engineering Geology, 2013a, 162, 14-21.
82. Kadali, S., Singh, D.N. and Shekhawat, S.K. “Application of X-ray Diffraction Analysis for Determining Residual Stresses on Soil Particles due to Thermal Treatment”, Journal of Testing and Evaluation, ASTM International, 2014, 42(5). 1240–1247.

83. Kadali, S., SushaLekeshmi, SU, Sharma, S. and Singh, D.N., “Investigations to Establish the Influence of the Thermal Energy Field on Soil Properties”, ACTA GEOTECHNICA SLOVENICA, 2013b, 10(2), 59-76.

84. Kadali, S., SushaLekshmi S.U., Singh, D.N. and Maryam Shojaei Baghini, M.S., “Application of Heat of Wetting for Determination of Soil Specific Characteristics of Fine-grained Soils”, Journal of Testing and Evaluation, ASTM, 2016, 44(6), DOI: 10.1520/JTE20150308.

85. Kannan, I.R., Jayanth, S., Gurnani, S. and Singh, D.N., “Influence of Initial Water Content and Specimen Thickness on the SWCC of Fine-grained Soils”. International Journal of Geomechanics, 2013, 13(6), 894-899.

86. Kaya, A. and Yukselen, Y., “Zeta Potential of Clay Minerals and Quartz Contaminated by Heavy Metals”, Canadian Geotechnical Journal, 2005, 42(5), 1280-1289.

87. Kaya, A., Ören A.H. and Yükselen Y., “Settling of Kaolinite in Different Aqueous Environment”, Marine Georesources and Geotechnology, 2006, 24(3), 203-218.

88. Ketterings, Q.M., Bigham, J.M. and Laperche, V., “Changes in Soil Mineralogy and Texture Caused by Slash and Burn Fires in Sumatra, Indonesia”, Soil Science Society of American Journal, 2000, 64(3), 1108-1117.

89. Kibsgaard, G. D. B., “Environmental Geotechnics-The Art of Crossing Boundaries”, Environmental Geotechnics, 2016, 3(5), 291-292.

90. Kolay, P.K. and Singh, D.N., "Effect of Zeolitization on Compaction, Consolidation and Permeation Characteristics of a Lagoon Ash", Journal of Testing and Evaluation, ASTM, 2000, 28(6), 425-430.

91. Kolay, P.K. and Singh, D.N., “Application of Coal Ash in Fluidized Thermal Beds”, Journal of Materials in Civil Engineering, ASCE, 2002a, 14(5), 441-444.

92. Kolay, P.K. and Singh, D.N., “Characterization of An Alkali Activated Lagoon Ash and its Application for Heavy Metal Retention”, Fuel, 2002b, 81(4), 483-489.

93. Kolay, P.K. and Singh, D.N., “Effect of Zeolitization on Physicochemico-Mineralogical and Geotechnical Properties of Lagoon Ash”, Canadian Geotechnical Journal, 2001b, 38(5), 1105-1112.

94. Kolay, P.K. and Singh, D.N., “Physical, Chemical, Mineralogical and Thermal Properties of Cenospheres from a Ash Lagoon”, Cement and Concrete Research, 2001a, 31(4), 539-542.
95. Kolay, P.K., Singh, D.N. and Murti, M.V.R., “Synthesis of Zeolites from a Lagoon Ash”, Fuel, 2001, 80(5), 739-745.

96. Koshy, N. and Singh, D.N., “Fly ash Zeolites for Water Treatment Applications”, Journal of Environmental Chemical Engineering, 2016a, 4(2), 1460-1472.

97. Koshy, N. and Singh, D.N., “Textural Alterations in Coal Fly Ash due to Alkali Activation”, Journal of Materials in Civil Engineering, ASCE, 2016b, 28 (11), 04016126.

98. Koshy, N., Jha, B., Kadali, S. and Singh, D.N., “Synthesis and Characterization of Ca and Na Zeolites (non-pozzolanic materials) Obtained from Fly Ash-Ca(OH)_2 Interaction”, Materials Performance and Characterization, ASTM International, 2015a, 4(1), 87-102.

99. Koshy, N., Singh, D.N., Jha, B., Kadali, S. and Patil, J., “Characterization of Na and Ca Zeolites Synthesized by various Hydrothermal Treatments of Fly Ash”, Advances in Civil Engineering Materials, ASTM International, 2015b, 4(1), 131-143.

100. Koshy, N., Sushalekshmi, S.U., Sharma, S., Joseph, J., Sharma, V., Singh, D.N., Jha, B. and Singh, M., “Characterization of the Soil Samples from the Lonar Crater, India”, Geotechnical Engineering Journal of the SEAGS & AGSSEA, 2018, 49(1), 99-105.

101. Kosoglu, L., “Environmental Geotechnics-A Geotechnical Engineer’s View”, Environmental Geotechnics, 2014, 1(2), 70.

102. Krishnaiah, S. and Singh, D.N., “A Device for Determination of Thermal Properties of Soil”, Journal of Testing and Evaluation, ASTM, 2004a, 32(2), 114-119.

103. Krishnaiah, S. and Singh, D.N., “A Methodology to Determine Soil Moisture Movement Due to Thermal Gradients”, Journal of Experimental Thermal and Fluid Science, 2003b, 27(6), 715-721.

104. Krishnaiah, S. and Singh, D.N., “Centrifuge modelling of Heat Migration in Soils”, International Journal of Physical Modeling in Geotechnics, 2004b, 4(3), 39-47.

105. Krishnaiah, S. and Singh, D.N., “Determination of Influence of Various Parameters on Thermal Properties of Soils,” International Communications in Heat and Mass Transfer, 2003a, 30(6), 861-870.

106. Krishnaiah, S. and Singh, D.N., “Determination of Thermal Properties of Some Supplementary Cementing Material Used in Cement and Concrete”, Construction and Building Materials, 2006a, 20(3) 193-198.

107. Krishnaiah, S. and Singh, D.N., “Determination of Thermal Properties of Soils in a Geotechnical Centrifuge”, Journal of Testing and Evaluation, ASTM, 2006b, 34(4), 319-326.

108. Krishnaiah, S., Singh, D.N. and Jadhav, G.N., “A Methodology for Determining Thermal Properties of Rocks”, International Journal of Rock Mechanics and Mining Sciences, 2004, 41, 877-882.
109. Kulkarni, M.P., Patel, A. and Singh, D.N., “Application of Shear Wave Velocity for Characterizing Clays from Coastal Regions”, KSCE Journal of Civil Engineering, 2010, 14(3), 307-321.

110. Kumar, P.R. and Singh, D.N., "A Novel Technique for Monitoring Contaminant Transport Through Soils", Environmental Monitoring and Assessment, 2005, 109(1-3), 147-160.

111. Kumar, R.P. and Singh, D.N., “Geotechnical Centrifuge Modeling of Chloride Diffusion through Soils”, International Journal of Geomechanics, 2012, 12(3), 327-332.

112. Liu, Y., “Influence of Heating and Water-exposure on the Liquid Limits of GMZ01 and MX80 Bentonites”, Journal of Rock Mechanics and Geotechnical Engineering, 2010, 2(2), 188-192.

113. Mahjoub, M. and Rouabhi, A., “Modelling of Anisotropic Damage due to Hydrogen Production in Radioactive Waste Disposal”, Environmental Geotechnics, 2018, 5(3), 176-183.

114. Manthena, K.C. and Singh, D.N., “Centrifuge Modeling of Soil Thermal Resistivity”, International Journal of Physical Modeling in Geotechnics, 2001, 1(4), 29-34.

115. Marti, J., “Whence and Whereto?”, Environmental Geotechnics, 2015, 1(3), 135.

116. Meenu, P.S., Sowmya, S., Latha, R.A., Shashank, B.S. and Singh, D.N., “Investigations on Influence of Bio-Geo Interface on Suction Characteristics of Fine-Grained Soil”, Geotechnical and Geological Engineering, 2017, 35(2), 607-614.

117. Moayed, H., Asadi, A., Moayed, F. and Huat, B.B.K., “Zeta Potential of Tropical Soil in Presence of Polyvinyl Alcohol”, International Journal of Electrochemical Science, 2011, 6(5), 1294-1306.

118. Moghal, A.A.B., Reddy, K.R., Mohammed, S.A.S., Al-Shamrani, M.A. and Zahid, W.M., “Sorptive Response of Chromium (Cr^{6+}) and Mercury (Hg^{2+}) from Aqueous Solutions using Chemically Modified Soils”, Journal of Testing and Evaluation, ASTM, 2017, 45(1), 105-119.

119. Mohamed, A.-M. O., “Towards Sustainable Development Practices in Geoenvironmental Engineering”, Environmental Geotechnics, 2015, 2(4), 189-190.

120. Mondal, S., Dangayach, S. and Singh, D.N., “Establishing Heat-Transfer Mechanisms in Dry Sands”, International Journal of Geomechanics, ASCE, 2018a, 18(3), 06017024.

121. Mondal, S., Padmakumar, G.P., Sharma, V., Singh, D.N. and Baghini, M.S., “A Methodology to Determine Thermal Conductivity of Soils from Flux Measurement”, Geomechanics and Geoengineering: An International Journal, 2016, 11(1), 73-85.

122. Mondal, S., Sharma, V., Apte, P. and Singh, D.N. “Electrical analogy for modelling thermal regime and moisture distribution in sandy soils”, Geomechanics and Geoengineering: An International Journal, 2018, 13(1), 22-32.
123. Mondal, S., Sharma, V., Singh, D.N. and Baghini, M.S., “Detection of Thermal Response of Geomaterials: A Critical Appraisal”, Emerging Materials Research, 2018, 7(3), 1-14.

124. Mondal, S., Sharma, V., Singh, D.N. and Baghini, M.S., “Determination of Thermal Regime in Sandy Soils: A Mathematical Framework ‘ATHERES’, International Journal of Geomechanics, ASCE, 2017, 17(9), 04017045.

125. Mualem, Y., “A New Model for Predicting Hydraulic Conductivity of Unsatuated Porous Media”, Water Resource Research, 1976, 12, 593-622.

126. Palaparthy, V., Singh, D.N. and Baghini, M.S., “Compensation of Temperature Effects for In-situ Soil Moisture Measurement by DPHP Sensor”, Computers and Electronics in Agriculture, 2017, 141, 73-80.

127. Palaparthy, V.S., Baghini, M.S. and Singh, D.N., “Review of Polymer-Based Sensors for Agriculture-Related Applications”, Emerging Materials Research, 2013, 2(4), 166-180.

128. Parlak, M., “Effect of Heating on Some Physical, Chemical and Mineralogical Aspects of Forest Soil”, Journal of the BartınOrmanFakültesiDergisi, 2011, 1(3(19)), 143-152.

129. Patel, A. and Singh, D.N., “A Generalized Relationship for Estimating Shear Wave Velocity in Soils”, International Journal of Geotechnical Engineering, 2009, 3(3), 343-351.

130. Patel, A., Bartake, P.P. and Singh, D.N., “An Empirical Relationship for Determining Shear Wave Velocity in Granular Materials Accounting for Grain Morphology”, Geotechnical Testing Journal, ASTM, 2009, 32(1), 1-10.

131. Patel, A., Kulkarni, M.P., Bartake, P.P., Rao, K.V. and Singh, D.N., “A Methodology for Determination of Resilient Modulus of Asphaltic Concrete”, Advances in Civil Engineering, Special issue on Advances in Instrumentation and Monitoring in Geotechnical Engineering, 2011, 1, 936395.

132. Patel, A., Singh, D.N. and Singh, K.K., “Performance Analysis of Piezoceramic Elements in Soils”, Geotechnical and Geological Engineering, 2010, 28, 681–694.

133. Patel, A., Singh, K.K. and Singh, D.N., “Application of Piezoceramic Elements for Determining Elastic Properties of Soils”, Geotechnical and Geological Engineering, 2012, 30, 407-417.

134. Patent No.: 277842. A methodology for Determination of Swelling Properties of Soils from Suction Measurements (Indian Patent Application No. 2579/MUM/2012), Granted 2016.

135. Patent No.: 277862. A Novel method for Determining Cracking Characteristics of Fine-grained Soils Using Laser Microscopy (Indian Patent Application No. 2578/MUM/2012), Granted 2016.

136. Patent No.: 297124. A Methodology to Determine Influence of Initial Water Content and Specimen Thickness on the SWCC of Fine-grained Soils (Indian Patent Application No. 2040/MUM/2013), Granted 2018.
137. Pathak, P., Singh, D.N., Apte, P.R. and Pandit, G.G., “Statistical Analysis for Prediction of Distribution Coefficient of Soil-contaminant System”, Journal of Environmental Engineering, 2016b, 142(1), 04015054.

138. Pathak, P., Singh, D.N., Pandit, G.G. and Apte, P.R., “Establishing Sensitivity of Distribution Coefficient on Various Attributes of Soil-contaminant System”, Journal of Hazardous, Toxic and Radioactive Waste, ASCE, 2014a, 18(1), 64-75.

139. Pathak, P., Singh, D.N., Pandit, G.G. and Rakesh, R.R., “Determination of Distribution Coefficient: A Critical Review”, International Journal of Environment and Waste Management, 2014b, 14(1), 27-64.

140. Pathak, P., Singh, D.N., Pandit, G.G. and Rakesh, R.R., “Quantification of Geomaterial-Contaminant Interaction: Some Guidelines”, Journal of Hazardous, Toxic, and Radioactive Waste Management, ASCE, 2016a, 20(1), 04015012.

141. Patil, B.S. and Singh, D.N., “Study of Sustainable Engineered Bioreactor Landfill (SEBL) for Small Communities”, The Journal of Solid Waste Technology and Management, 2015, 14, 1-14.

142. Patil, B.S., Anto, A. and Singh, D.N., “Simulation of Municipal Solid Waste Degradation in Aerobic and Anaerobic Bioreactor”, Waste Management & Research, 2017, 35(3), 301-312.

143. Pellet, F. L., “Underground Urban Development and Geoenvironmental Issues”, Environmental Geotechnics, 2017, 4(1), 1-2.

144. Penumadu, D., Dutta, A. K., Luo, X. and Thomas, K. G., “Nano and Neutron Science Applications for Geomechanics”, KSCE Journal of Civil Engineering, 2009, 13(4), 233-242.

145. Poulose, A., Smitha, R. Nair. and Singh, D.N., "Centrifuge Modelling of Moisture Migration in Silty Soils", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2000, 126(8), 748-752.

146. Prakash, K., Sridharan, A. and Sudheendra, S., “Hygroscopic Moisture Content: Determination and Correlations”, Environmental Geotechnics, 2016, 3(5), 292-301.

147. Rajeev, K.P. and Singh, D.N., “Instrumentation and Testing Methodology for Detecting Cl-Contaminants in Soils”, Journal of Testing and Evaluation, ASTM, 2004, 32(2), 81-87.

148. Rajesh, S., Rao, H.B., Sreedeep, S. and Arnepalli, D.N., “Environmental Geotechnology: An Indian Perspective”, Environmental Geotechnics, 2015, 2(6), 336-348.

149. Rakesh, R.R., Singh, D.N. and Nair R.N., “Soil-Radionuclide Interaction under Varied Experimental Conditions”, Journal of Hazardous, Toxic, and Radioactive Waste, ASCE, 2017, 21(1), D4015005.

150. Rakesh, R.R., Singh, D.N. and Nair, R.N., “A Methodology for Simulating Radionuclide Diffusion in Unsaturated Soils”, Geotechnical and Geological Engineering, 2009, 27(1), 13-21.
151. Rao, B.H. and Singh, D.N., “Establishing SWCC and Determination of Unsaturated Hydraulic Conductivity of Kaolin by Ultra Centrifugation and Electrical Measurements”, Canadian Geotechnical Journal, 2012, 49(12), 1369-1377.

152. Rao, B.H., Bhat, A.M. and Singh, D.N., “Application of Impedance Spectroscopy for Modeling Flow of AC in Soils”, Geomechanics and Geoengineering: An International Journal, 2007b, 2(3), 197-206.

153. Rao, B.H., Dalinaidu, A. and Singh, D.N., “Accelerated Diffusion Test on the Intact Rock Mass”, Journal of Testing and Evaluation, ASTM, 2007a, 35(2), 111-117.

154. Rao, B.H., Venkataramana, K. and Singh, D.N., “Studies on determination of swelling properties of soils from suction measurements”, Canadian Geotechnical Journal, 2011, 48(3), 375-387.

155. Rao, H.B. and Singh, D.N., “Determination of Diffusion Characteristics of Intact Rock Mass: A Critical Evaluation”, Geotechnical Testing Journal, 2008, 31(6), 490-502.

156. Rao, S.M., Rao, P. R. and Malini, R., “Environmental Geotechnics: Need for Regional Approach”, Environmental Geotechnics, 2014, 1(1), 66-67.

157. Reddy, K. R., “Evolution of Geoenvironmental Engineering”, Environmental Geotechnics, 2015, 1(3), 136-141.

158. Reddy, K.R. and Adams, J.A., “Effects of Soil Heterogeneity on Air Flow Patterns and Hydrocarbon Removal During In-situ Air Sparging”, Journal of Geotechnical and Geoenvionmental Engineering, 2001, 127(3), 234-247.

159. Reddy, K.R., Chinthamreddy, S., Saichek, R.E. and Cutright, T.J., “Nutrient Amendment for the Bioremediation of a Chromium-contaminated Soil by Electrokinetics”, Energy Sources, 2003, 25(9), 931-943.

160. Reddy, K.R., Kulkarni, H.S., Giri, R.K. and Khire, M.V., “Horizontal Trench System Effects on Leachate Recirculation in Bioreactor Landfills”, Geomechanics and Geoengineering: An International Journal, 2017a, 12(2), 115-136.

161. Reddy, K.R., Kumar, G. and Giri, R.K., “Influence of Dynamic Coupled Hydro-bio-mechanical Processes on Response of Municipal Solid Waste and Liner System in Bioreactor Landfills”, Waste Management, 2017b, 63, 143-160.

162. Reddy, N.G., Rao, B.H. and Reddy, K.R., “Biopolymer Amendment for Mitigating Dispersive Characteristics of Red Mud Waste”, Géotechnique Letters, 2018, 8(3), 1-24.

163. Rohini, K. and Singh, D.N., “A Methodology for Determination of Electrical Properties of Soils”, Journal of Testing and Evaluation, ASTM, 2004, 32(1), 64-70.
164. Rouf, M.A., Singh, R.M., Bouazza, A., Rowe, R.K. and Gates, W. P., “Gas Permeability of Partially Hydrated Geosynthetic Clay Liner Under two Stress Conditions”, Environmental Geotechnics, 2016, 3(5), 325-333.

165. Rowe, R.K., “Performance of GCLS in Liners for Landfill and Mining Applications”, Environmental Geotechnics, 2014, 1(1), 3-21.

166. Rowe, R.K., “Reflections on the Evolution of Geoenvironmental Engineering”, Environmental Geotechnics, 2015, 2(2), 65-67.

167. Sarhosis, V., Hosking, L.J. and Thomas, H.R., “Carbon Sequestration Potential of the South Wales Coalfield”, Environmental Geotechnics, 2018, 5(4), 234-246.

168. Shah, P. and Singh, D.N., “Generalized Archie’s Law for Estimation of Soil Electrical Conductivity”, Journal of ASTM International, 2005, 2(5), 1-20.

169. Shah, P.H. and Singh, D.N., “A Simple Methodology for Determining Electrical Conductivity of Soils”, Journal of ASTM International, 2004, 1(5), 1-11.

170. Shah, P.H. and Singh, D.N., “Methodology for Determination of Hygroscopic Moisture Content of Soils”, Journal of ASTM International, 2006, 3(2), 1-14.

171. Shah, P.H., Sreedeep, S. and Singh, D.N., “Evaluation of Methodologies Used for Establishing Soil-Water Characteristic Curve”, Journal of ASTM International, 2006, 3(6), 1-11.

172. Shankara, N., Prakash, B.S. and Sivapullaiah, P.V., “Removal Efficiencies of Iron from Different Soils During Different Processes of Electro-kinetic Extraction, Pollution Research, 2016, 35(1), 97-105.

173. Shanthakumar, S., Singh, D.N. and Phadke, R.C., “Determining Residual Ammonia in Flue Gas Conditioned Fly Ashes and its Influence on the Pozzolanic Activity”, Journal of Testing and Evaluation, ASTM, 2011, 39(1), 69-76.

174. Shanthakumar, S., Singh, D.N. and Phadke, R.C., “Flue Gas Conditioning for Reducing Suspended Particulate Matter from Thermal Power Stations”, Progress in Energy and Combustion Science, 2008a, 34(6), 685-695.

175. Shanthakumar, S., Singh, D.N. and Phadke, R.C., “Influence of Flue Gas Conditioning on Fly ash Characteristics”, FUEL, 2008b, 87, 3216-3222.

176. Shanthakumar, S., Singh, D.N. and Phadke, R.C., “Methodology for Determining Particle-Size Distribution Characteristics of Fly Ashes”, Journal of Materials in Civil Engineering, ASCE, 2010, 22(5), 435-442.

177. Shanthakumar, S., Singh, D.N. and Phadke, R.C., “The Effect of Dual Flue Gas Conditioning on Fly Ash Characteristics”, Journal of Testing and Evaluation, ASTM, 2009, 37(6), DOI: 10.1520/JTE102267.
178. Sharma, S. and Singh, D.N., “Characterization of Sediments for Sustainable Development: State of the Art”, Marine Georesources and Geotechnology, 2015, 33(5), 447-465.

179. Sharma, S., Meenu P.S., Asha Latha R., Shashank B.S. and Singh, D.N., “Characterization of Sediments from the Sewage Disposal Lagoons for Sustainable Development”, Advances in Civil Engineering Materials, ASTM International, 2016, 5(1), 1-23.

180. Shashank, B.S., Minto, James M., Singh, D.N., GráinneElMountassir and Knapp, C. W., “Guidance for Investigating Calcite Precipitation by Urea Hydrolysis for Geomaterials”, Journal of Testing and Evaluation, ASTM, 2018, 46(4), 1945-7553.

181. Shashank, B.S., Sharma, S., Sowmya S., Asha Latha R., Meenu P.S. and Singh, D.N., “State-of-the-Art on Geotechnical Engineering Perspective on Bio-mediated Processes”, Environmental Earth Sciences, 2016, 75(3), DOI: 10.1007/s12665-015-5071-6.

182. Shetty, R. and Singh, D.N., “Rheological Characteristics of Fine-Grained Soil-Slurries”, Journal of Testing and Evaluation, ASTM, 46(6), 2018, https://doi.org/10.1520/JTE20170035. ISSN 0090-3973.

183. Shetty, R. and Singh, D.N., “Utilization of Dredged Sediments: Contemporary Issues”, Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, 2017, 143(3), 04016025.

184. Shetty, R., Zhang, X., Coussot, P. and Singh, D.N., “A "Complex Fluid" Approach for Determining Rheological Characteristics of the Fine-Grained Soils and Clay Minerals”, Journal of Materials in Civil Engineering, 2018, 30(12), Paper no. 04018322.

185. Shinde, S.B., Kala, V.U., Kadali, S., Tirumkudulu, M.S. and Singh, D.N., “A Novel Methodology for Measuring the Tensile Strength of Expansive Clays”, Geomechanics and Geoengineering: An International Journal, 2012, 7(1), 15-25.

186. Simkovic, I., Dlapa, P., Doerr, S.H., Mataix-Solera, J. and Sasinkova, V., “Thermal Destruction of Soil Water Repellency and Associated Changes to Soil Organic Matter as Observed by FTIR spectroscopy”, Catena, 2008, 74(3), 205-211.

187. Singh, D.N. and Devid, K., “Generalized Relationships for Estimating Soil Thermal Resistivity”, Experimental Thermal and Fluid Science, 2000, 22, 133-143.

188. Singh, D.N. and Gangadharma Rao, M.V.B.B., “Laboratory Determination of Soil Thermal Resistivity:”, Geotechnical Engineering Bulletin, 1998, 7(3), 179-189.

189. Singh, D.N. and Gupta, A.K., "Falling-head Conductivity Tests in a Geotechnical Centrifuge", Journal of Testing and Evaluation, ASTM, 2001, 29(3), 258-263.

190. Singh, D.N. and Gupta, A.K., "Modelling hydraulic conductivity in a small centrifuge", Canadian Geotechnical Journal, 2000,37(5), 1150-1155.
191. Singh, D.N. and Kolay, P.K., "Simulation of Ash-Water Interaction and Its Influence on Ash", Progress in Energy and Combustion Science, 2002, 28, 267-299.

192. Singh, D.N. and Kuriyan S.J., “Estimation of Unsaturated Hydraulic Conductivity Using Soil Suction Measurements Obtained by an Insertion Tensiometer”, Canadian Geotechnical Journal, 2003, 40(2), 476-483.

193. Singh, D.N. and Kuriyan, S.J., “Estimation of Hydraulic Conductivity of Unsaturated Soils Using a Geotechnical Centrifuge”, Canadian Geotechnical Journal, 2002, 39(3), 684-694.

194. Singh, D.N., “Editorial”, Environmental Geotechnics, 2014, 1(1), 1-2.

195. Singh, D.N., “‘From ‘Nowhere to Somewhere’, The Mind of an Engineer, Ghosh, P. and Raj B. (Eds.), 2016, 143-147. Springer.

196. Singh, D.N., Devid, K. and Naidu, A.D., “Fabrication of Thermal Probes for Estimation of Soil Thermal Resistivity”, Journal of Testing and Evaluation, ASTM. 31(1), (2003), 65-72.

197. Singh, D.N., Kolay, P.K. and Rao, A.K., “A New Approach to Study Leaching of Fly Ash from Landfills”, The Journal of Solid Waste Technology and Management, 2002, 28(3), 138-144.

198. Singh, D.N., Kuriyan, S.J. and Chakravarthy, M., “A Generalized Relationship between Soil Electrical and Thermal Resistivities”, Journal of Experimental Thermal and Fluid Science, 2001, 25(3-4), 175-181.

199. Singh, D.N., Kuriyan, S.J. and Madhuri, V., "Application of a Geotechnical Centrifuge for Estimation of Unsaturated Soil Hydraulic Conductivity”, Journal of Testing and Evaluation, ASTM, 2001, 29(6), 556-562.

200. Singh, K.K., Singh, D.N. and Ranjith, P.G., "Effect of Sample Size on the Fluid Flow through a Single Fractured Granitoid", Journal of Rock Mechanics and Geotechnical Engineering, 2016, 8(3), 329-340.

201. Singh, K.K., Singh, D.N. and Ranjith, P.G., “Laboratory Simulation of Flow through Single Fractured Granite”, Rock Mechanics and Rock Engineering, 2015, 48(3), 987-1000.

202. Singh, K.K., Singh, D.N. and Ranjith, P.G., “Simulating Flow through Fractures in a Rockmass Using Analog Material”, International Journal of Geomechanics, 2014, 14(1), 8-19.

203. SoilVision 4.18, “A Knowledge-based Database System for Soil Properties”, SoilVision Systems Ltd., Saskatoon, Saskatchewan, Canada. 2005.

204. Sowmya, S. Meenu, P.S., Asha Latha, R. and Singh, D.N., “Laboratory Investigations on the Effects of Bacteria on Fine-Grained Soils”, Advanced Engineering Forum, 2017, 21, 352-357.

205. Sreedeeep, S. and Singh, D.N., “A Critical Review of the Methodologies Employed for Soil Suction Measurement”, International Journal of Geomechanics, ASCE, 2011, 11(2), 99-104.
206. Sreedeep, S. and Singh, D.N., “A Novel Technique for Studying Diffusion of Contaminants in Fine-Grained Soils”, Geomechanics and Geoengineering: An International Journal, 2008, 3(3), 199-209.

207. Sreedeep, S. and Singh, D.N., “A Study to Investigate Influence of Soil Properties on Its Suction”, Journal of Testing and Evaluation, ASTM, 2005a, 31(1), 579-584.

208. Sreedeep, S. and Singh, D.N., “Estimating Unsaturated Hydraulic Conductivity of Fine-Grained Soils Using Electrical Resistivity Measurements”, Journal of ASTM International, 2005b, 2(1), DOI: 10.1520/JAI12823

209. Sreedeep, S. and Singh, D.N., “Methodology for Determination of Osmotic Suction of Soils”, Geotechnical and Geological Engineering, 24(5), 2006a, 469-479.

210. Sreedeep, S. and Singh, D.N., “Nonlinear Curve-Fitting Procedures for Developing Soil-water Characteristic Curves”, Geotechnical Testing Journal, ASTM, 2006b, 29(5), 409-418.

211. Sreedeep, S., Reshma, A.C. and Singh, D.N., “Measuring Soil Electrical Resistivity Using a Resistivity Box and a Resistivity Probe”, Geotechnical Testing Journal, ASTM, 2004, 27(4), 411-415.

212. Sreedeep, S., Reshma, A.C. and Singh, D.N., “Generalized Relationship for Determining Soil Electrical Resistivity from its Thermal Resistivity”, Experimental Thermal and Fluid Science, 2005, 29, 217-226.

213. Sultan, N., Delage, P. and Cui, Y.J., “Temperature Effects on the Volume Change Behavior of Boom Clay”, Engineering Geology, 2002, 64(2-3), 135-145.

214. Sushe Lekshmi S.U., Prathyusha, J.N.V., Aravind. P., Singh, D.N. and Bhagini, M.S., “A Critical Analysis of the Performance of Plate- and Point-electrodes for Determination of Electrical Properties of the Soil mass”, Measurement, Journal of the International Measurement Confederation, 2016, 93, 552-562.

215. Sushe Lekshmi S.U., Singh, D.N. and Baghini, M.S., “A Critical Review of Soil Moisture Measurement”, Measurement, 2014, 54, 92-105.

216. Sushe Lekshmi S.U., Singh, D.N., Tarantino, A. and Baghini, M.S., “Evaluation of the Performance of TDR and Capacitance Techniques for Soil Moisture Measurement”, Geotechnical Testing Journal, ASTM, 2018b, 41(2), 292-306.

217. Sushe Lekshmi S.U., Singh, D.N., Tarantino, A. and Baghini, M.S., “Investigations on Magnetic Characteristics of the Soil and their Influence on its Dielectric Response”, Applied Clay Science, 2018a, 158, 113-122.

218. Taguchi, G. and Konishi, S., “Taguchi methods, orthogonal arrays and linear graphs: Tools for quality engineering”, American Supplier Institute, Dearborn, MI. 1987.
219. Tan, Ö., Yilmaz, L. and Zaimoğlu, A.S., “Variation of Some Engineering Properties of Clays with Heat Treatment”, Materials Letters, 2004, 58(7-8), 1176-1179.

220. Tanaka, N., Graham, J. and Crilly, T., “Stress-strain Behaviour of Reconstituted Illitic Clay at Different Temperatures”, Engineering Geology, 1997, 47(4), 339-350.

221. Tej, P.R. and Singh, D.N., “Estimation of Tensile Strength of Soils from Penetration Resistance”, International Journal of Geomechanics, 2013, 13(5), 496-501.

222. Thakur, V.K.S. and Singh, D.N., “Rapid Determination of Swelling Pressure of Clay Minerals”, Journal of Testing and Evaluation, ASTM, 2005, 33(4), 239-245.

223. Thakur, V.K.S., Sreedeep, S. and Singh, D.N., “Evaluation of Various Pedo-Transfer Functions for Developing Soil Water Characteristic Curve for a Silty Soil”, Geotechnical Testing Journal, ASTM 2007, 30 (1), 25-30.

224. Thakur, V.K.S., Sreedeep, S. and Singh, D.N., “Laboratory Investigations on Extremely High Suction Measurements for Fine-grained Soils”, Geotechnical and Geological Engineering, 2006, 24(3), 565-578.

225. Thakur, V.K.S., Sreedeep, S. and Singh, D.N., “Parameters Affecting Soil Water Characteristic Curves of Fine-grained Soils”, Journal of Geotechnical and Geoenvironmental Engineering, 2005, 131(4), 521-524.

226. Tripathy, S., “Engineering Societal Issues-Geotechnical and Geoenvironmental Perspectives”, Environmental Geotechnics, 2015, 2(5), 253-254.

227. Uday, K.V. and Singh, D.N., “Application of Laser Microscopy for Studying Crack Characteristics of Fine-grained Soils”, Geotechnical Testing Journal, ASTM, 2013a, 36(1), 146-154.

228. Uday, K.V. and Singh, D.N., “Investigations on Cracking Characteristics of Fine-grained Soils under Varied Environmental Conditions”, Drying Technology, 2013b, 31(11), 1255-1266.

229. Uday, K.V., Prathyusha J.N.V., Singh, D.N. and Apte, P. R., “Application of Taguchi Method in Establishing Criticality of Parameters that Influence Cracking Characteristics of Fine-grained Soils”, Drying Technology, 2015, 33(9), 1138-1149.

230. Uday, K.V., Prathyusha, J.N.V. and Singh, D.N., “A Generalized Relationship for Determination of Tensile Strength of Fine-grained Soils from Shrinkage Characteristics”, Drying Technology, 2014, 32, 869-876.

231. Ulery, A.L. and Graham, R.C., “Forest Fire Effects on Soil Color and Texture”, Soil Science Society of American Journal, 1993, 57(1), 135-140.

232. Van Genuchten, M. T., “A Closed form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils”, Soil Society of America Journal, 1980, 44, 892-898.
233. Vane, L.M. and Zhang, G.M., “Effects of Aqueous Phase Properties on Clay Particle Zeta Potential and Electro-osmotic Permeability: Implications for Electro-kinetic Soil Remediation Processes”, Journal of Hazardous Materials, 1997, 55(1-3), 1-22.

234. Venkataramana, K., Rao, B., H. and Singh, D.N., “A Critical review of the Methodologies Employed for Determination of Tensile Strength of the Fine-grained Soils”, Journal of Testing and Evaluation, ASTM, 2009, 37(2), 115-121.

235. Wang, X.S., “Batch Sorption of Lead (II) from Aqueous Solutions using Natural Kaolinite”, International Journal of Environment and Waste Management, 2011, 8(3-4), 258-272.

236. Welzel, U., Ligot J., Lamparter P., Vermeulen A.C. and Mittemeijer E.J., “Stress Analysis of Polycrystalline Thin Films and Surface Regions by X-ray Diffraction”, Journal of Applied Crystallography, 2005, 38(1), 1-29.

237. West, L.J. and Stewart, D.L., “Effect of Zeta Potential on Soil Electrokinesis”, Geoenvionment 2000, ASCE Special Publication 46, 1995, 1535-1549.

238. Witthüser, K., Dalinaiu, A. and Singh, D.N., “Investigations on Diffusion Characteristics of Granite and Chalk Rock Mass”, Geotechnical and Geological Engineering, 2006, 24(2), 325-334.

239. Wu, X.F. and Zhou, G., “Application of improved Taguchi method to the multi response optimization”, Industrial Engineering and Engineering Management, IEEE 18th Int. Conf., Institute of Electrical and Electronics Engineers, Beijing, China, 2011, 3, 1829-1832.

240. Yilmaz, G., “The Effects of Temperature on the Characteristics of Kaolinite and Bentonite”, Scientific Research and Essays, 2011, 6(9), 1928-1939.

241. Yukselen, Y. and Kaya, A., “Zeta Potential of Kaolinite in the Presence of Alkali, Alkaline Earth and Hydrolyzable Metal Ions”, Journal of Water, Air and Soil Pollution, 2003, 145(1-4), 155-168.

242. Yun, T.S. and Santamarina, J.C., “Fundamental Study of Thermal Conduction in Dry Soils”, Granular Matter, 2008, 10(3), 197-207.

243. Zhang, Y., Miao, L. and Wang, F., “Study on the Engineering Properties of the Stabilized Mucky Clay as Backfill Material in Highway Embankment Projects”, Geo-Frontiers 2011: Advances in Geotechnical Engineering, ASCE, 2011, 1365-1371.