Article:

Tang, C-S, Paleologos, EK, Vitone, C et al. (2020) Environmental Geotechnics: Challenges and Opportunities in the Post COVID-19 World. Environmental Geotechnics. pp. 1-21. ISSN: 2051-803X

https://doi.org/10.1680/jenge.20.00054

Accepted manuscript
doi: 10.1680/jenge.20.00054

Accepted manuscript

As a service to our authors and readers, we are putting peer-reviewed accepted manuscripts (AM) online, in the Ahead of Print section of each journal web page, shortly after acceptance.

Disclaimer

The AM is yet to be copyedited and formatted in journal house style but can still be read and referenced by quoting its unique reference number, the digital object identifier (DOI). Once the AM has been typeset, an 'uncorrected proof' PDF will replace the 'accepted manuscript' PDF. These formatted articles may still be corrected by the authors. During the Production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to these versions also.

Version of record

The final edited article will be published in PDF and HTML and will contain all author corrections and is considered the version of record. Authors wishing to reference an article published Ahead of Print should quote its DOI. When an issue becomes available, queuing Ahead of Print articles will move to that issue's Table of Contents. When the article is published in a journal issue, the full reference should be cited in addition to the DOI.

Downloaded by [] on [30/04/20]. Copyright © ICE Publishing, all rights reserved.

Submitted: 18 April 2020

Published online in 'accepted manuscript' format: 28 April 2020

Manuscript title: Environmental Geotechnics: Challenges and Opportunities in the Post COVID-19 World

Authors: Chao-Sheng Tang[1], Evan K Paleologos[2], Claudia Vitone[3], Yan-Jun Du[4], Jiang-Shan Li[5], Ning-Jun Jiang[6], Yong-Feng Deng[4], Jian Chu[7], Zhengtao Shen[8], Eugeniusz Koda[9], Andrea Dominijanni[10], Xunchang Fei[7,11], Magdalena Daria Vaverková[9,12], Piotr Osiński [9], Xiaohui Chen[13], Afshin Asadi[14], Maria RH Takeuchi[15], Myint Win Bo[16], Hossam Abuel-Naga[17], Eng-Choon Leong[7], Arvin Farid[18], Tugce Baser[19], Brendan C. O' Kelly[20], Bhagwanjee Jha[21], Venkata Siva Naga Sai Goli[22], Devendra N. Singh[22]

Affiliations: [1]School of Earth Sciences and Engineering, Nanjing University, Nanjing, China. [2]Department of Civil Engineering, Abu Dhabi University, Abu Dhabi, UAE. [3]DICATECh Department, Politecnico di Bari, Italy. [4]Institute of Geotechnical Engineering, School of Transportation, Southeast University, Nanjing, China. [5]State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China. [6]Department of Civil and Environmental Engineering, University of Hawaii at Manoa, Honolulu, HI, USA. [7]School of Civil & Environmental Engineering, Nanyang Technological University, Singapore. [8]Department of Earth and Atmospheric Sciences, University of Alberta, Canada. [9]Institute of Civil Engineering, Warsaw University of Life Sciences - SGGW, Poland. [10]Department of Structural, Geotechnical & Building Engineering, Politecnico di Torino, Turin, Italy. [11]Residues & Resource Reclamation Centre, Nanyang Environment and Water Research Institute, Singapore. [12]Faculty of AgriSciences, Mendel University in Brno, Czech Republic. [13]School of Civil Engineering, University of Leeds, UK. [14]Civil Engineering Discipline, International College of Auckland, Auckland, New Zealand. [15]Graduate School of Energy Science, Kyoto University, Kyoto, Japan. [16]Bo & Associates Inc., Mississauga, Ontario, Canada. [17]School of Engineering and Mathematical Sciences, La Trobe University, Victoria, Australia. [18]Civil Engineering, Boise State University, Boise, ID, USA. [19]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, USA. [20]Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland. [21]Department of Civil Engineering, Dr. B.B.A. Govt. Polytechnic, Karad (DP), Dadra and Nagar Haveli, Silvassa, India. [22]Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India.

Corresponding author: Chao-Sheng Tang, School of Earth Sciences and Engineering, Nanjing University, Nanjing, China. Tel.: 86-25-83597888

E-mail: tangchaosheng@nju.edu.cn

Abstract

The outbreak of the COVID-19 pandemic not only created a health crisis across the world but is expected to negatively impact the global economy and societies at a scale that maybe larger than the 2008 financial crisis. Simultaneously, it has inevitably exerted many negative consequences on the geoenvironment upon which human beings depend. The current article articulates the role of environmental geotechnics to elucidate and mitigate the effects of the current pandemic. It is the belief of all authors that the COVID-19 pandemic presents significant challenges, but also opportunities for the development of our field. Our discipline should make full use of our professional skills and expertise to look for development opportunities from this crisis, to highlight our discipline's irreplaceable position in the global fight against pandemics, and to contribute to the health and prosperity of our communities, so as to better serve humankind. In order to reach this goal, while taking into account the specificity of the SARS-CoV-2 and the uncertainty of its environmental effects, it is believed that more emphasis should be placed on the following research directions: pathogen-soil interactions, isolation and remediation technologies for pathogen-contaminated sites, new materials for pathogen-contaminated soil, recycling and safe disposal of medical wastes, quantification of uncertainty in geoenvironmental and epidemiological problems, emerging technologies and adaptation strategies in civil, geotechnical, and geoenvironmental infrastructure, pandemic-induced environmental risk management, and model pathogen transport and fate in geoenvironment, among others. Moreover, COVID-19 has made it clear to the environmental geotechnics community the importance of urgent international cooperation

and of multidisciplinary research actions that must extend to a broad range of scientific fields, including medical and public health disciplines, in order to meet the complexities posed by the COVID-19 pandemic.

Introduction

An extremely infectious new coronavirus, known as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has led to the spread of coronavirus disease 2019 (COVID-19) across the world, infecting more than 2.5 million people, as confirmed by WHO on April 24, 2020. Many countries have been forced to close borders and routes, with many cities implementing quarantine measures, and workplaces, schools, and universities shut down. Lockdowns are managed to stop people from traveling and participating in social activities. The daily lives of billions of people have been disrupted with half the world under stay-home orders (NY Times, Friday, April 3, 2020) and the global economy expected to suffer historic losses.

On the other hand, this pandemic has also brought a first-time realization that our common fate can only be secured by coordinated global action, which has quickly been followed by acts of allegiance among countries (WHO, 2020). Scientific collaboration and knowledge transmission have proceeded during these weeks with unmatched speed, where health officials in a European country, like Greece, may be quoting the preliminary results announced a few hours earlier by the Chinese Academy of Science (iefimerida, Friday, April 3, 2020, *"New experimental medicine offers hope,"* in Greek), or comparing in real-time their public health measures to those of other countries. Rapid transmission of scientific information across borders has been a key factor during the fight against the pandemic and will be essential to assess the lessons learned from this traumatic experience when it is over.

The objective of the current article is to appraise, albeit in a preliminary fashion, what the broader scientific community has learned from the experience of the COVID-19 pandemic. Given that global-scale threats exist not only in the health domain but also in the environmental domain, with the global climate change looming prominent in the horizon, this article presents lessons learned about the urgency of developing new knowledge, of taking actions, and of modifying policy protocols in order to cope with fast-evolving, global situations.

Environmental geotechnics provides a unique blend of principles of geotechnical engineering, geomechanics, and environmental sciences. It has long been dedicated to using multi-disciplinary perspectives, techniques, and methods to solve environmental-related geotechnical engineering problems. Our mission is to protect the geological environment on which human society and ecosystems rely on for their existence, to safeguard human health from pollution events and disasters, and to take measures and actions in order to provide clean air, pure water, uncontaminated soil, and renewable and sustainable energy so that current and future generations can lead healthy and beautiful lives. However, with the outbreak of this pandemic, the raging virus is challenging the mission and efforts of environmental geotechnics. Therefore, in the middle of this challenge, we've turned to ourselves and asked "How can our discipline better serve our society, fulfill our duties, and make the world a better place for present and future generations? What can we do now? What's there in the future for environmental geotechnics?"

In response to the COVID-19 outbreak, the authors of this article believe that environmental geotechnics should strengthen research in the following areas: pathogen-soil interactions, pathogen migration, diffusion mechanisms in soil pores, and effects on soil engineering properties; in-situ isolation and remediation technologies for pathogen-contaminated sites; new materials development for rapid disinfection of pathogen contaminated soil; recycling and safe disposal of medical solid wastes. Effort should be devoted into international cooperation and interdisciplinary research, such as cross-disciplinary research in environmental geotechnics, public health, microbiology, medicine, and other related disciplines. Especially in the area of cross-disciplinary research, the characteristic of environmental and geotechnical problems to exhibit large temporal and spatial uncertainties has led to the development of new and the refinement of existing techniques to quantify uncertainty. Bayesian probabilistic models are especially suitable for geoenvironmental analyses with their capability to make use of soft information and to subsequently incorporate and update new knowledge as it becomes available. These models appear also to be the preferred ones for COVID-19 epidemiological studies (Flaxman et al., 2020). In addition, emerging technologies, and adaptation strategies in infrastructure management, pandemic-induced environment risk management, and modeling of pathogen transport in the geoenvironment are important research topics. Concentrated, coordinated and cooperative research efforts on these areas will provide new perspectives that will contribute to the welfare of our society, counter the multi-faceted effects of COVID-19, plan ahead and prepare for similar events in the future.

Impact of environmental geotechnics to endure challenges

Pathogen-soil interactions

The deadly and highly infectious SARS-CoV-2 is among many other pathogens (i.e., bacterium, protozoan, prion, viroid, or fungus) that have become a major public health concern worldwide. While how pathogens are transmitted through human beings and animals, and how they are associated with different diseases are being continuously and extensively investigated by microbiologists, epidemiologists and public health experts, it still remains largely unknown how pathogens interact with the geoenvironment from an engineering perspective. Soils are very complex ecosystems composed of various physical, chemical, and biological components. Like many aerobic and anaerobic microorganisms that can live within the vadose zone or in deeper saturated layers, various pathogens may be able to live, reside, adapt or even evolve within the soil environment. Hence, they can become part of a cycle that can bring them and their resulting pandemics back to the surface. On the opposite end of the health spectrum, soils host many ingredients that have helped humans combat various diseases, e.g., antibiotics and medications. Interactions and potential effects of pathogens on the physical processes and engineering properties of soils must be well understood. Therefore, there is a pressing need to address issues including pathogen detection and their implications in the geoenvironment.

(1) *Detection of pathogens in soils and sediments:* Detection of pathogens in different environments is the first step to assess their risks. In microbiology, there are already a handful of techniques that can identify or quantify pathogens in soils and sediments including culture-based and molecular-based detection methods. While these techniques are basic skills to microbiologists, they are still unfamiliar to most geoenvironmental researchers and engineers. Culture-based methods are usually used to obtain isolates of pathogens, but they are labor-intensive and not able to detect non-cultivable cells. Unlike culture-based methods, molecular-based methods detect specific DNA segments of the pathogens' genome, which provides high specificity and accuracy. Polymerase chain reaction (PCR) and sequencing-based approaches are two major groups of molecular-based methods. While these techniques are continuously being improved, there are still many challenges when dealing with soil and sediment samples. The reliable analysis of pathogens in soils and sediments requires accuracy, specificity, sensitivity, reproducibility, and cost-effectiveness. However, high microbial diversity and low concentration of target pathogens in the geoenvironment pose great challenges for selecting appropriate detection and delineation methods. Therefore, a thorough understanding of the features of mainstream detection methods is critically important.

(2) *Antibiotic resistance of pathogens and its implication for the geo-environment:* A vaccine is thought to be the most effective way to defeat the pathogenic coronavirus for the COVID-19 pandemic. However, for the treatment and prevention of pathogenic infection,

especially pathogenic bacterial infection, antibiotics are frequently used. To date, the excessive use of antibiotics in many countries has led to the accumulation of antibiotic resistance genes (ARGs) in infectious bacteria, which has become a severe public health issue. ARGs from natural sources are rare except in ancient pristine permafrost sediments. However, anthropogenic sources of ARGs from hospitals, wastewater plants, and farms have resulted in a significant increase in antibiotic resistance of pathogenic bacteria in soils, because bacteria are exposed to a sub-inhibitory concentration of antibiotics. Therefore, it is imperative for the geoenvironmental community to take action to understand the existence of antibiotic-resistant infectious bacteria in soils.

(3) *Modification of soil engineering properties by pathogens:* Many microbes in nature have been found to be capable of altering soil physicochemical properties. For example, ureolytic bacteria, such as *S. Pasteurii,* are able to hydrolyze urea and produce calcite precipitation in the soil pores to improve the strength of sandy soils (Jiang et al. 2019, 2020). Nevertheless, there has been very limited research on how pathogens could potentially alter the engineering performance of soils. Pathogenic bacteria and fungi are likely to change soil physicochemical properties through their own metabolic activities (forming extracellular polymeric substance (EPS), generating gas, changing the redox environment, altering ambient acidity-alkalinity condition, etc.). These will, in turn, affect the mechanical, hydraulic and/or physicochemical behavior of soils. On the other hand, pathogenic viruses are not likely to affect soil properties directly, as their size is too small (1/100 of most bacteria), and they die quickly if they are not in an infected cell. However, they are likely to affect soil properties through their infected host cells, which could be animals, plants, bacteria, archaea, etc., by changing their physiological behavior. This is a new frontline area that deserves exploration by the geoenvironmental community.

(4) *Soil erosion and dust control:* As pathogenic microbes can stick to surfaces and transmitted in the air through suspended dust particles, soil erosion needs to be reduced and dust control should be advanced so that the transport of pathogens in the air is hindered. In that respect, some yet unpublished studies have suggested a potential correlation between air pollution from $PM_{2.5}$ and COVID-19 health risks (Harvard T.H. Chan School of Public Health 2020). Hence, more publicity is required to increase awareness of the detrimental consequences of soil erosion and related dust problems, in addition to no littering, and more research needs to be conducted in order to develop easily applied methods for erosion reduction and dust control. Recently some microbial geotechnical techniques have been developed for erosion and dust control (Chu et al. 2012; Dejong et al. 2013; Stabnikov et al. 2013; Tang et al., 2020). However, the use of bacteria for experimental purposes in actual in-situ conditions can be sensitive. Alternatively, enzymes can be used instead, and enzyme or polymer-based methods have also been developed in recent years (Khatami and O'Kelly, 2013; Cheng et al. 2019; He et al. 2020).

(5) *Learning from municipal solid waste (MSW) studies:* MSW and soil share many common characteristics. For instance, they are both multi-phase geomaterials with solid skeletons and have intermixed liquid and gas phases. Microorganisms are almost omnipresent in soils (Mitchell and Santamarina 2005), whereas MSW is laden with microorganisms as well (Barlaz et al. 1989, Weaver et al. 2019). Scientists and engineers have studied MSW-microorganism interactions for decades and have taken advantage of certain biochemical processes in engineering practices (Reinhart and Townsend 1998). Therefore, learning from peer MSW industry is beneficial and convenient for soil-pathogen interactions. It is beneficial as many properties and processes of interest are similar between soil- and

MSW-microorganism interactions. In the context of pathogens, we would like to highlight some (non-exhaustive) relevant studies that stem from MSW research as follows:

- Characterization methods for microbial communities in MSW and leachate (Bareither et al. 2013, Fei et al. 2015, Staley et al. 2011).
- Modeling long-term biochemical and other associated processes in MSW landfills (Gawande et al. 2010, McDougall 2007).
- Existence and transport of ARGs in landfilled MSW (Song et al. 2016, Wu et al. 2017), leachate (Yu et al. 2016), and the surrounding environment (Chen et al. 2017).
- Airborne microorganisms in and adjacent to landfills (Heo et al. 2010, Kalwasińska and Burkowska 2013).
- Interactions between microorganisms and the geosynthetics that are used as a containment system (Gallagher 1998, Palmeira et al. 2008).
- Existence, transport and fate of pathogenic prion protein (Jacobson et al. 2009) and avian influenza virus (Graiver et al. 2009) in landfill system.
- Identification of sources of pathogens in landfills (Gerba et al. 2011).

Containment and remediation technologies for pathogen-contaminated sites

Containment

The procedure prior to soil remediation generally includes site environmental investigation, risk assessment, and design of the remediation strategy. Understanding pathogen transport in soils is essential for taking countermeasures to contain pathogen-laden wastewater and to remediate pathogen-contaminated soil and/or groundwater. The transport of pathogens in soils has been extensively addressed in the realm of soil science. Studies have shown that the degree of saturation of soil, void ratio, exchangeable cations, pH and hydraulic conductivity of soil, ionic strength of soil pore fluid, amount of organic surface functional groups of soil particles, and temperature are important factors influencing the retention of pathogens in soils (Bitton and Harvey, 1992; Potts et al., 2004). Transport of pathogens in soils can be modeled using a modified advection-dispersion theory with consideration of the die-off rate of pathogens, whereas mass transfer of pathogens between solid and aqueous phases in soils can be modeled by a first-order attachment/detachment equation (Morales et al., 2014; Zhang et al., 2013). Organic matter in soils has been found to favor the adsorption of bacteria onto soils. In contrast, the presence of soil organic matter decreases the adsorption of viruses. The presence of clays, hematite, and magnetite increases virus retention (Bitton and Harvey, 1992).

Survival of pathogenic viruses in soils is closely related to the hydraulic properties and purification capacity of the soil for microorganisms, which mainly refers to the adsorption and lethal ability of a specific soil to pathogenic microorganisms, with this process denoted as “natural purification” (Zhao, 2006; Xiao and Zhao, 2006). This effect depends on various factors, such as soil hydraulic conductivity, virus type, pH, ionic strength and multivalent cations, organic matter, temperature, soil water content, microparticles, microbial activity, among others (Katan, 2017; Malham et al., 2014). Reducing the migration ability of viruses, enhancing the adsorption and fixation of a virus, and accelerating the rate of virus inactivation are main treatment purposes for soils with a relatively weak purification ability, so as to prevent the virus from breaking through the soil purification barrier and further contaminate the groundwater.

SARS-CoV-2 entering the soil may come into contact with human beings and become a source of recurrent infection, before becoming inactive. The diagram in Fig.1 shows the trace of pathogens in water systems, while ruptures in landfill and sewage pipes can introduce pathogens into soils (Wigginton et al., 2015). Therefore, it is essential to strengthening the surveillance of each link and the preparation of emergency measures.

In particular, hospitals and healthcare facilities use buried pipelines, for draining pathogen-laden wastewater, and containers, for temporally storing pathogen-laden wastewater. Potential leakage of such buried pipes and containers may result in contamination of soils and groundwater. Installation of barriers including HDPE geomembranes (GMs), geosynthetic clay liners (GCLs), compacted clay liners (CCLs), and composite liners underlying the pipelines and containers are expected to control the flow of leaked wastewater in soils, and reduce the environmental impact on groundwater quality. Geomembrane/GCL composite liner is much more effective than a geomembrane/CCL composite liner in mitigating leakage through defects in geomembranes (Rowe et al., 2004). Vertical barriers, such as soil-bentonite slurry trench walls, overlapped deep mixed columns, or geomembrane/GCL composite walls may be needed to contain plume of pathogen impacted groundwater or to isolate the concentrated pathogen-laden waste water that leaks into soils (Rowe et al., 2004; Wu et al., 2020). Clearly, the economic feasibility of providing double containment systems for all underground sewage systems, which all contain pathogens (not only from hospitals), must be assessed. Nevertheless, as of today, very limited studies have systematically investigated the following issues:

(1) Can the hydraulic conductivity of underground barrier systems be altered by the permeation with pathogen-laden wastewater?

(2) What will be the durability and service life of geomembranes that are exposed to pathogen-laden or sanitizer-laden wastewater?

(3) How can transport parameters, die-off rates, and mass transfer between solid and aqueous phases of the pathogenic bacterium through GM, GCLs, and CCLs be determined?

(4) What can environmental geotechnical professionals do to develop novel leakage detection methods without excavation of pathogen impacted in-situ ground soils?

Particular caution is needed in dealing with potential leakages of wastewater containing soap, as soap is found to be able to reduce soil surface tension and may enhance transport of wastewater through GCLs, CCLs, vertical barriers or natural soils in the vadose zone (Rowe et al., 2004). Modified GCLs or new additives to CCLs are needed if the hydraulic conductivity of conventional GCLs or CCLs to pathogen-laden wastewater is found to exceed commonly accepted limits (Yang et al., 2018), and die-off rate of the pathogen in GCLs or CCLs is of concern. To obtain transport parameters and die-off rates of pathogens, especially of pathogenic viruses from lab-scale tests, environmental geotechnical professionals may need help from medical and public health professionals on conducting experiments in special laboratories with acceptable human health exposure risks. Advice from legal professional, may also be needed, to ensure the legitimacy of certain laboratory experiments.

Remediation

(1) *Microbial approach:* The wide application of microbial technology in environmental and geotechnical engineering may contribute to the development of emergency measures of virus-contaminated sites. It has been reported that microbial activities have a certain effect on the survival of viruses in soils, and the die-off rate of the virus in sterilizing media is obviously lower than that in non-sterilizing media (Artur and Nigel, 2004). Quanrud et al. (2003) elucidated that the possible mechanisms for microbe-mediated virus attenuation were the excretion of soluble microbial products, which can degrade virions and utilize viruses as a growth substrate. It has also been suggested that microbial life activities and enzymes promote virus inactivation through chemical and physical environmental changes, induced by microbial metabolism (Decrey and Kohn, 2017). The role of microorganisms mentioned above must be closely related to the characteristics of the SARS-CoV-2, and the selection or injection of microorganisms to contaminated soils requires a joint effort from virology researchers.

By introducing or activating the metallogenic microorganisms and providing corresponding reactants in the soil, nano-grade biological minerals can be produced to occupy part of the pores in soils and strongly adsorb the virus. This approach can reduce the solute migration distance of the virus in the soil and reduce the pollution range, especially, when the mineralized products are metal oxides, such as iron oxides, which have proved to have a strong sorption and inactivation effect on the virus (Chu et al., 2001). Moreover, biomineralization has a short reaction time and high metallogenic efficiency. Thus, it can also be applied to provide adsorption sites of the bio-flocculants for the virus in water-contaminated areas.

Some researchers have shown that ammonia could effectively kill single-stranded RNA (SS-RNA) virus (Decrey et al., 2015). Due to their ability to hydrolyze urea efficiently and thus produce ammonia, urease microorganisms are expected to be used in the disinfection of contaminated soils and groundwater. Moreover, the byproduct, ammonia, can be further converted into environmentally friendly substances, such as guano stone and nitrogen, to avoid secondary pollution of the environment.

(2) *Stabilization/Solidification:* Solidification/Stabilization (S/S), as an environmental geotechnical technology, has been widely used to remediate contaminated soils through chemical fixation and physical encapsulation/adsorption. Considering the characteristics of the SARS-CoV-2, S/S can also be applied in SARS-CoV-2 contaminated soils. Appropriate reagents should be selected to quickly inactivate and stabilize the virus, followed by rapid solidification and encapsulation, which can cut off the transmission routes and achieve a good remediation effect. Based on the current prevention and control measures in China, the disinfection and stabilization reagents for inactivation of the SARS-CoV-2 mainly include 1000 mg/L chlorine-containing disinfectant or 75% alcohol, acid peroxide, and hydrogen peroxide. Breidablik et al (2020) recommended that ozonized water could be used as an

alternative. Using the aforementioned reagents to treat pathogenic virus-contaminated soils is referred to as soil stabilization. Nonetheless, the presence of these reagents may impact the survival conditions of autochthonous bacteria in soils. In addition, overdosage of chlorine-containing disinfectants in soils may cause adverse impacts if the remediated soils are reused as construction materials. In view of solidifying pathogenic virus-contaminated soils, magnesium phosphate cement (MPC), geopolymer and other types of novel binders with high early strength, low permeability and diffusivity, and high resistance to climate change can be considered (Qiao et al.,2010; Jiang et al., 2018; Wu et al., 2018; Haque and Chen, 2019; Xia et al., 2019a, b; Du et al., 2020; Zhang et al.,2020). Special efforts can be made by introducing additives capable of enhancing the die-off rate of pathogenic viruses in soils. Although we have a large number of S/S remediation experiences, the synergistic mechanism on the disinfection of the SARS-CoV-2 is still unclear. Furthermore, for lab-scale tests in order to screen appropriate reagents and optimize dosages, as well as for field demonstration tests to validate the feasibility of the S/S technique, environmental geotechnics professionals need to combine efforts with researchers from virology, public health, medical epidemiology, and even jurisprudence of medicine. Quality control/quality assurance and environmental and human health risk control measures in the construction and reuse of treated soil are also challenging tasks to be met by our discipline.

(3) *Groundwater remediatio*n: The improper use of medical waste devices and the leakage of medical wastewater can cause wastewater containing pathogens to pollute groundwater through soil infiltration (Xu et al., 2020). Casanova and Weaver (2015) suggested that the envelope virus could survive in sewage for 6-7 days. Hence, it is indispensable to treat groundwater suspected to contain pathogenic microorganisms. If necessary, the groundwater contaminated with SARS-CoV-2 in centralized isolation areas or hospitals can be pumped out

for treatment to eliminate viruses. Hydrogeologists should assist in determining the optimal remediation conditions of contaminated sites.

For pumped groundwater, adsorbents with positive charge should be considered for the removal of the virus (Zhan et al., 2014). Shen et al. (2010) utilized bacteriophage phiX174 as the virus indicator, demonstrating that nanoparticles alpha-Fe_2O_3 achieved a nearly 100% adsorption rate for low-concentration viruses (1E+03 PFU.mL^{-1}). Mazurkow et al (2020) prepared spray-dried alumina granules, modified with copper (oxide) nanoparticles, to assess the effect of copper oxidation state on virus removal capacity. These authors showed that copper (I) oxide and metallic copper were the active phases in virus removal and 99.9% of MS2 bacteriophages could be removed. Although current adsorbents are excellent in adsorbing pathogenic microorganisms, the preparation process is often cumbersome and costly, and clay or mineral waste-based adsorbents should be considered as alternatives.

Photocatalysis has also been widely used for in-situ treatment of groundwater containing pathogenic contamination. Materials containing TiO_2 can decompose oxygen into hydroxyl groups (•OH) and superoxide anions (O^{2-}) under ultraviolet (UV) irradiation, which may destroy the structure of viruses and play a disinfecting role. Cui et al (2010) showed that the anatase nano -TiO_2 sol was effective to eliminate the H_9N_2 avian influenza virus (aiv) under UV irradiation of wavelength of 365 nm. The ectopic treatment of pathogen-contaminated wastewater by photocatalysis can be achieved by groundwater extraction through a light-transmissive reaction column equipped with catalytic materials.

In addition to the above methods, the use of reverse osmosis membrane (RO), with a pore size of 0.5nm-10nm, as filter material can also remove bacteria and viruses in contaminated groundwater. The synergy of environmental geotechnical and membrane treatment expertise may improve this treatment technology. In addition, to avoid secondary pollution and protect public health, the treatment of material derived from wastewater treatment processes also needs to be considered.

The above ideas are only at the incubation stage. The role of environmental geotechnics should be enhanced by the efforts in contaminated soil remediation, and actively carry out research on technologies to remediate SARS-CoV-2 contaminated soils. More importantly, it is necessary to investigate the problems arising from the remediation of contaminated soils by this virus. Safeguard procedures should be followed during remediation to avoid infection. Targeted remediation activities and field experiments must be carried out jointly by geoenvironmental engineering, virology, and material science researchers to establish well-defined protocols that address both health and legal issues.

Development of new materials for remediation of pathogen-contaminated soil

The SARS-CoV-2 can enter the soil and groundwater by a range of pathways: the disposal and discharge of solid and fluid medical wastes, the discharge of patient and suspects feces, which were found to contain SARS-CoV-2 (Xu *et al.*, 2020), and the sputum from suspects and those infected people who have not been detected. The SARS-CoV-2 was reported to live from 4 to 72 hours on environmental surfaces, depending on the nature of the surface material (van Doremalen *et al.*, 2020). But a recent report from the US Centers for Disease Control and Prevention (CDC) suggested that the virus can survive for 17 days in the environment (Moriarty, 2020). Therefore, the transport and spread of the virus via soil and groundwater can be a serious issue. Researchers and practitioners of environmental geotechnics should make efforts to reduce the pathways of the virus in the soil and groundwater in order to limit the exposure of potential receptors. Especially in “hot-spot” areas, where patients and suspected cases may be concentrated, the groundwater, if needed, could be pumped and treated to eliminate the virus. Technologies such as adsorption, photocatalytic degradation, and microfiltration can be used to remove the virus from the pumped water. If contaminated groundwater, which is also suspected to contain the virus, flows through an existing permeable reactive barrier (PRB), new materials can be added to the PRB to remove the virus from the groundwater. In "hot-spot" areas, additives could also be amended to the soil to immobilize the virus and thus avoid its transport and spread. For all these scenarios, the key is to develop efficient materials for the removal of the virus from the geoenvironment. Electrokinetics Geosynthetics (EKG) could also be considered for drainage in such cases.

Environmental geotechnics community should develop high-performance sorbents that can adsorb the virus from groundwater (in pump-and-treat and PRB systems) or immobilize it in the soil. Most viruses are negatively charged under typical environmental pH conditions (Zhan *et al.*, 2014). The adsorption of viruses to a sorbent can be affected by the surface charge, hydrophobicity and surface properties of the pathogens, and the surface area and property of sorbents (Zhan et al., 2014). Zhan et al. (2014) used amino to modify Fe_3O_4–SiO_2 which possess protonic amino groups with a cationic charge so that the prepared magnetic Fe_3O_4–SiO_2–NH_2 nanoparticle can adsorb the negatively charged virus. As a positively charged sorbent, layered double hydroxides (LDHs) have shown excellent performance in removing anionic contaminants (Yu *et al.*, 2017), and they therefore are potentially feasible for the adsorption of SARS-CoV-2. Modification or composite fabrication based on existing geotechnical sorbents (e.g., zeolite, clay minerals, and biochar) may be a solution to develop efficient new sorbents for the virus.

One of the research topics to pursue is the investigation of the usability of biochar in the absorption of pathogens from contaminated sediments (Wang et al., 2019). The efficacy of activated carbon has been already studied as sorbent to viruses and bacteria (Cookson, 1969; Meynet et al., 2012 Sasidharan et al., 2016). The attraction is due to electrostatic forces between the pathogens and carbon. Effects of pH and ionic strength indicated that carboxyl groups, amino groups, and the virus's tail fibres are involved in its attachment to carbon. Such studies can modify ongoing experiments on the adsorption of heavy metals and organic pollutants, but should also involve researchers from biology and medicine and should implement multiscale tests. They have to be carried out from the microscale, to follow the processes inducing adsorption at the base of the phenomena, to the in-situ scale, to check the efficacy of the treatment from the short-term to the long-term. The possibility of using modified or anti-bacterial/virus geotextile filters can also be investigated (Silva and Palmeira, 2019).

Materials that help to decompose, degrade, and destroy the virus are also needed for the treatment of pumped suspected groundwater. $La_2Mo_2O_9$ was observed to decrease the survival rates of bacteriophage Qβ and bacteriophage Φ6 by more than 99.9% (Matsumoto *et al.*, 2019). Several solid-state cuprous compounds, including oxide (Cu_2O), sulfide (Cu_2S), iodide (CuI), and chloride ($CuCl_2$) were shown to effectively kill viruses within 0.5 or 1 hours (Sunada *et al.*, 2012). Therefore, environmental geotechnics community should work together with material scientists and engineers to develop novel and effective materials to eliminate the SARS-CoV-2 from the geoenvironment.

Biogeotechnical engineering has been applied in erosion control and slope stabilization. Biotechnology has recently been applied in the remediation of petrochemical contaminated soils by releasing bacteria that consume high volumes of diesel during their life span into the diesel contaminated soils. Transportation of bacteria and nutrition for such bacteria along the flow paths in order to make them travel farther and to extend their life span has been tried through electrokinetic processes for soil pH stabilization (Hassan et.al., 2016). Laboratory and field small-scale pilot tests have been completed successfully. In addition, it may be possible to clone suitable bacteria that will consume viruses in situ or to investigate organic or inorganic substances that may neutralize the effect of SARS-CoV-2.

Safe disposal of SARS-CoV-2 infected material

Disposal of medical and municipal SARS-CoV-2 infected waste

SARS-CoV-2 is a huge challenge not only for the world of medicine. For scientists outside the health field, an important fact is that increasing numbers of hospitals, clinics, and other medical institutions are generating massive amounts of medical waste (MW). The production of new types of waste that may contain pathogens, such as municipal solid waste (MSW) from households with people in isolation, who are tested positive to the virus, or people in mandatory quarantine, or discarded masks and gloves mixed with household waste, requires extraordinary measures for the protection of the professionals involved in the collection and disposal of this waste (Carducci *et al*., 2013). It also raises issues for the sorting and separation of materials from MSW during these times, and the recycling of products that may have originated from household materials contaminated with the virus. The amount of MSW has also significantly increased lately due to the high demand and storage of food products that eventually degrades.

MSW contaminated with the SARS-CoV-2 can be treated in the same way as regular MW. Presently, two processes are usually adopted for MW destruction (*e.g.* ILD, 1997 or MEEC, 2020), (i) high-temperature steam sterilization and landfilling after crushing (MEEC, 2006); (ii) incineration and landfilling of the resulting fly and bottom ash (MEEC, 2003).

Incineration is the most technically and economically feasible option, which is applicable to all types of MW, with significant quantity reduction (Deng et al., 2014; Steen and Su-Ling, 2015; Makarichi et al., 2018). This method has been widely applied in developed countries and will be the mainstream method to deal with MW in developing countries in the future (Fang et al., 2020). However, in the current situation of the global pandemic, the question remains whether enough MW or MSW incineration plants exist in each country with sufficient capacity to process all contaminated waste. In some countries, such as Poland, MSW incineration plants are still in the development stage, and under the current conditions, the designed capacity may prove to be insufficient. The current emergency circumstances could lead to inappropriate methods in waste storage and disposal, thus resulting in environmental and public health threats. In addition, are there enough MSW disposal installations in countries outside Europe and United States? And what is it going to happen if contaminated with SARS-CoV-2 waste is added, originating from households with members tested positive and quarantined? These questions have further increased the uncertainty and challenges in overcoming the pandemic. A potential solution may be to use existing industrial facilities for hazardous waste by modifying them and increasing the sanitary standards of their operation (Vaverkova *et al*., 2019). In many countries it has been decided that the waste company should determine the method or place to store, collect, and dispose of such waste, at the same time taking measures to minimize the risk to workers who manage waste, but also to other citizens. These are just some of the questions that scientists in the field of waste management will have to deal with in the near future.

Although MW after sterilization and incineration no longer pose health threats, as the infectivity, perniciousness, and vulnerability are eliminated, their disposal and recycling during this pandemic is challenging due to the following reasons:

(1) *Need to manage a large volume of MW in the short-term*. A rapid increase of MW production by as much as six times normal conditions has been observed in China, Poland, and the Czech Republic. In Italy, temporary disposal areas have been authorized to cope with the emergency, and specific guidelines have been issued to manage medically-contaminated waste into existing landfills (MW must be inserted

into big-bags, deposited in specific zones of the landfill, and covered daily with a layer of soil adequate thickness to avoid dispersion in the air).

(2) *Increased ecological concern on the landfill waste mass*. During the pandemic the type and composition of the MSW have changed and MW accounts for a greater proportion of the disposed mass. Due to these changes, the potential impact on the microecology inside the landfills and on the waste degradation process should be considered. Furthermore, the service life and performance of the containment lining system should be re-evaluated. Previous sections of this article delve extensively into this issue.

(3) *Random disposal of MW by public*. Although masks and gloves used at hospitals can be collected and managed using proper protocols, it is highly improbable that when disposed by the public at random locations they could be similarly dealt with. Hence, the presence of these materials in MSW could lead to a substantial change in the composition of MSW, especially in plastic fractions that may end up in material recycling facilities, composting yards, and landfills. It would be prudent to conduct socio-economic analyses on the recycling of these fractions by adopting proper disinfecting schemes.

(4) *Need for recycling fly and bottom ash.* In China, incineration in cement kilns is explored as an option for treating MW by using a temperature higher than 1350 °C (Wang *et al.*, 2018). The MW, which is part of the raw materials is first calcined to make clinker, adjusted by gypsum, and pulverized into grains smaller than 50 μm to form ordinary Portland cement. In the cement industry, the stability and component variability are strictly controlled and therefore the consumption of MW is limited. However, to address the current emergency, a possible innovation could be to use the

clinker with more MW as a binder for soil modification/stabilization applications in order to consume large volumes of MW.

Waste transportation, reloading, and preparation of storage areas are other challenging issues with frequent decontamination needed to be implemented in the whole waste management chain. Referring to the latest updates from Netherlands (Mao *et al.*, 2020) on the presence of the virus in wastewaters, another challenge will be to safely manage potentially generated leachate or surface runoff from MW storage areas, to avoid further spread of the infection risk. A possible innovation in this field could be a special disposal container lined by a geomembrane with a leakage detection system to collect highly sensitive leachate and remote markers to trace the waste in the landfill for future detection, monitoring, and further investigation.

Preparation and maintenance of sites for safe and dignified disposal of casualties

In the history of mankind, there are a few pandemics similar to the COVID-19 where mass casualties had resulted. In such cases, cremation was the preferred method for disposal of the dead, but often the less desirable method of burial was selected because of unavailability of facilities and time. Still, often, as was observed on April 10, 2020, in New York City, existing graveyards may have insufficient capacity or some deceased people may not be claimed by relatives, and mass burial is used. The World Health Organization (WHO) has recommended guidelines for mass burials, but these guidelines have not incorporated the latest technologies that can help minimize health risks to workers that conduct burials, and the general public. Geosynthetic clay liners (GCL) can be employed to prepare burial sites and capillary barrier systems can be employed as capping, for the safe and dignified disposal of casualties to reduce the risk of contamination and deterioration in the future.

Geoenvironmental professionals have contributed to the prevention of public health threats by locating suitable sites for waste disposal, designing containment systems, selecting suitable covers, implementing monitoring systems, remediating contaminated land and groundwater (Bo 2011, 2014). In addition, they have contributed in the control and risk management of health outbreaks through the selection of suitable disposal sites that exhibit low underlying hydraulic conductivity. Such example includes the disposal of dead pigs that were contaminated with foot and mouth disease, during the 2001 UK outbreak, at sites with suitable subsurface formations, natural cover materials at nearby locations, etc. (Scudamore et al., 2002). Monitoring systems were implemented at these sites to continuously measure the pollution in the area. Another example is the H1N1 outbreak in US and Canada in 2009 where geoenvironmental engineers acted to design burial systems in a short period of time.

Emerging technologies and adaptation in geotechnical engineering

Importance of proper infrastructure functioning during the pandemic

While the COVID-19 outbreak left the world crippled, the significance of geostructures that support essential critical infrastructure to provide water, energy, transportation, and food have become apparent. The Cyber and Infrastructure Security Agency of USA (2020) has identified the essential-critical infrastructure as shown in Fig. 2, and environmental geotechnics principles lie along the lines to ensure sustainability and adaptability of this infrastructure to extraordinary conditions and environments such as the current curfew and lockdown around the world. It is therefore imperative that essential needs should be met without disruptions and relatively low labor-required maintenance during a lockdown. Consequently, solutions to the present and future challenges will greatly benefit from the advancement in areas such as: (1) sustainable and resilient infrastructure operations; (2) contactless and fast deployment sensing systems for field monitoring; (3) fast deployment of site investigation equipment in extreme environments; (4)

new-era materials such as geopolymers to replace Portland cement based concrete; and (5) artificial intelligence integrated field operations.

Civil infrastructure and its proper functioning are very critical to the wellbeing of our daily lives, but especially during the COVID-19 pandemic, where people are required to practice social distancing for their protection and to prevent the transmission of the virus. Within this, among other essentials, are core requirements for clean drinking water supply, wastewater treatment, and solid waste management and disposal systems for which environmental geotechnics plays central important roles for their achievement (Johnston and O'Kelly, 2016). Practicing social distancing can be compromised in cases where the supply of these basic requirements is intermittent or does not function properly. For example, an instance arose in Ireland where a drinking water supply system became contaminated, such that the tap water supply was not deemed fit for human consumption. In this case, drinking water was centrally supplied by tankers to the community by the local authority, but the collection of this water by individuals needing to go to the tankers and then bring the water back to their homes in containers put added risk and stress on these people, especially for those belonging to at-risk groups who had to self-isolate for their health safety. A similar situation took place in the city of Rio de Janeiro (https://en.mercopress.com/2020/01/16/contaminated-drinking-water-in-rio-run-on-bottled-water-in-supermarkets). This issue may become of importance to rural regions of poor countries, where clean water networks may not have been installed, and people may have to travel and congregate in order to obtain water from common, public sources.

Rapid geotechnical site investigation and construction for emergency health units

Chinese engineers are applauded for creating the miracle to construct a hospital equipped with more than 1500 inpatient rooms in Wuhan, China in 10 days. This is unlikely the last time that quick action will be needed by geotechnical, structural, and environmental engineers.

Devices that can be deployed quickly for urgent and emergency tasks and for getting soil and environmental quality data quickly included the Geo-Env-Mobility Measuring and Monitoring (GEM3) mobile station as shown in Fig. 3, which was developed at Nanyang Technological University (NTU), Singapore. This station is equipped with site investigation equipment such as CPT or SCPT, it can take soil samples and water samples rapidly, and can carry out geophysical tests, such as shear wave and electrical soil resistivity. It hosts a 3D LiDAR scanner for road and surrounding monitoring and can collect and transmit data back to the office almost in real time. It can also measure air quality-related parameters. Research is ongoing at NTU to enable the GEM3 mobile station to carry out in situ detection of contaminants or organics in the subsurface environment without the requirement for obtaining soil or water samples.

Novel foundation types and ground anchoring systems that can be constructed without using specialized equipment need to be developed to meet emergency situations, where time is of the essence for the construction of health facilities. Portland cement is normally used for this purpose. However, cement needs to cure for at least 14 days. Plastic could be a good substitute for small-scale, emergency use for soil treatment. When plastic waste (Polyethylene or Polypropylene) is heated up to a temperature of 170 °C, it melts into a liquid form and can be used to mix with soil. The bricks of mixed soil (shown in Fig. 4a) can harden in minutes and the treated soil has very high strength as shown in Fig. 4b. Plastic can be stored or transported easily. Only a hot bath mixer needs to be developed for small scale or massive production. Another innovative foundation type is the granular anchor (O'Kelly et al., 2014; Sivakumar et al., 2013) - to replace the conventional concrete ground-anchor for resisting pullout/uplift forces, compression forces and also provide ground improvement - which can be quickly installed and then immediately deployed for anchoring tented structures.

Potential detoxification of the SARS-CoV-2 by zeolite

The human body gets infected due to toxins present in the external environment, which results in acidosis of our body (Kiki Health, 2019). In the context of the ongoing pandemic, it has been learnt that the SARS-CoV-2 can enter the human mouth, rest at the throat for a few days, and finally move to the lungs (WHO, 2020a). It is also reported that the SARS-CoV-2 during its stay at the throat interacts with cells and forms new mucus. This may be a product of any possible reaction between the acidic surface (i.e. glucoprotein) of the virus and the available moisture at the throat. If removal of the virus from the throat area is explored, there may not be any serious threat to the human host, and human respiratory congestion and other related problems may be reduced within a few days from such viral infection event.

The shape and size of the virus is shown on the electron microscope image in Fig. 5, with the shape of the virus being round, elliptic or pleomorphic, and its size from around 20-30 nm (MedicineNet, 2020), to 60-140 nm (Cascella et al., 2020). Such size at the nanoscale range hints that the surface of the coronavirus is probably negatively charged (Verma et al., 2006). Also, the virus is having an outer envelope as glycoprotein, i.e. attached to amino acid chains (Mechref and Novotny 2007). This is why it remains with water droplets (i.e. positive molecules). Such reports about the coronavirus also substantiate that water droplets (i.e. size more or less than 5 microns, mucous, and saliva (e.g. Na^+, K^+, Cl^-), as well as, potentially, various infectious agents viz. bacteria, fungi, and viruses) that are present during sneezing, act as carriers of the virus from one person to another (Atkinson et al., 2009). Accordingly, it may be inferred that the virus may get neutralized in the water droplets. In this condition, the concentration of water H^+ ion may be more than the virus present in the agglomerate (i.e. sneezed out virus-water droplet).

In view of the above, in order to inactivate the nexus of a virus - water droplets, agglomerate (i.e. positive or neutral in nature) may get absorbed by use of a molecular sieve powder, i.e., clinoptilolite type natural pure zeolite (Jha and Singh, 2016; Kiki Health, 2019) having negatively charged channels and cages) as a detox (i.e. edible/chewable pallet) of zeolite powder (Kraljević Pavelić et al., 2018). As shown in Fig. 6, once absorption of a water droplet (having the virus) happens with conceptualized use of the zeolite (absorbent, cation exchanger) this would be identified as a detoxification process. However, such an application of zeolite as a detox for the targeted virus present in humans needs to be meticulously explored through proper experimentation, for a feasibility study, practically allowed zeolite dose, benefits and side effects etc. Thus the same knowledge and technologies that are studied for soil remediation can potentially be applied to develop products with medical or consumer product applications.

The aftermath of excessive sanitization on utilization of biosolids and agricultural activities

The sanitizers or disinfectants *viz.,* sodium hypochlorite (NaClO) and calcium hypochlorite ($(Ca(ClO)_2$ used during the COVID-19 pandemic consists of oxidizing groups viz., ClO^-, ClO_3^- and -OH which may raise the pH (up to 12.5) of the constituents of the geoenvironment during their interaction (Fukuzaki et al., 2006). Further, these disinfectants and sanitizers would most likely reach sewage treatment plants and irrigation canals in urban local bodies and rural areas respectively, which would lead to the disruption of environmentally friendly microorganisms along with the pathogens. In this context, the change in pH and redox conditions, by the presence of chlorine-based compounds and other disinfectants, may hamper the microorganisms' growth in the activated sludge, due to the breakage of their cell walls, and consequently negatively influence the performance of wastewater treatment systems. The presence of higher Na and Ca-based compounds and less treated and stabilized sewage could influence the characteristics of the sewage biosolids generated by these facilities, which have been used as manmade resources for sustainable practices (Sharma and Singh, 2015). The formation of Na^+ and Ca^{+2} complexes in the presence of organic matter, which is available in the biosolids, could further hinder the utilization of biosolids.

On the other hand, agricultural activities could be negatively impacted by the irrigation of crops with water contaminated with Na^+ and Ca^{+2} cations existing in the disinfectants, owing to an increase in sodium adsorption ratio (Rao et al., 2002). Further, salinity and sodicity of the irrigation water and consequently of agricultural soils contaminated with disinfectants could curtail the growth of nitrogen fixing bacteria (NFB) in soils and plant nodules. Hence, the presence of disinfectants on the abundance of NFB and nitrogen fixation capacity of soils should be investigated. In this regard, the effect of landfill-mined-soil-like fractions (LFMSF), obtained from landfill mining activity, would be worth trying in order to enhance the growth of NFB in soils contaminated with disinfectants and to promote the utilization of LFMSF for sustainable development (Chandana et al., 2020).

Paradigms of uncertainty quantification and disaster risk management

Environmental geotechnics and the challenge of complexity

Today, as never before, the famous question “Does the flap of a butterfly’s wings in Brazil set off a tornado in Texas?” by Lorenz (1963) should receive a positive answer. This question was introducing chaos theory, which was used initially to study the dynamics of turbulent flow, and which considered that even a small change in the initial conditions of a complex system may completely change the system’s response. As a result, for these systems, reliable predictions are only possible for specific time-windows (that depend on the physics of each problem) because the coupling between the several components and the boundary conditions of the system are highly variable across space and time (Abarbanel, 1997). The pandemic by SARS-CoV-2 could be seen as a complex system, such as coronaviruses (normally under control through vaccines) when entering the chaotic state. This means, in other terms, that we have lost the capability of short and long-term effective predictions, as illustrated in Fig. 7 (Ferreira, 2001; Vitone, 2019), because "*chaos destroys the reductionist dream, the dream that we have absolute power if we only know enough about the details*" (Baranger, 2002).

Environmental geotechnics, for example, when dealing with the management of polluted sites, is used to face with emblematic cases of different types of complex systems. However, it has been recognized that, at some scale and, in particular, at that of contaminated soils or sediments, these interconnected and open systems evolve far from equilibrium and become chaotic (Vitone et al., 2018). Thus, it was recognized by the US National Academies (1994) that the complexity of the geologic medium will determine the success of clean-up efforts, with pump-and-treat systems having a reasonable chance to remediate only homogeneous, single and multiple-layered geologic systems. The conclusion from the US National Academies based on the outcomes of the investigated sites was that for heterogeneous and fractured subsurface systems only partial cleanup is likely, with the more realistic goal being that of containment. This is particularly true because the soil or sediment environment is a habitat for microorganisms and viruses, and the characteristics of soils may modify the roles of viruses in biogeochemical nutrient cycles and as genomic reservoirs. Changes in environmental parameters, such as moisture content, temperature, pH, and aerobicity are a common occurrence in soils by weather and field management for better crop production (Kimura et al., 2008). Microorganisms in soils and sediments adapt to such environmental fluctuations by changing their physiology, and this can add further complexity to the understanding of the coupled processes occurring within them up to make them enter chaos. It follows that a reliable long-term engineering prediction of the soil and sediment mechanical and hydraulic behaviour can become difficult since it depends on the envisaged coupling between several components and the boundary conditions, which in turn are highly variable in space and time.

Environmental systems are, by definition, complex adaptive systems and the use of sustainable remedial strategies can induce these systems to come back operating at least at the so-called edge-of-chaos (Baranger, 2002). The edge-of-chaos is between stability and chaotic turbulence, where systems may produce again transient emergent orders (Dare, 2000; Waldrop, 1992), detectable through reductionism-based predictions. In addition, some recent advanced numerical tools have enabled the solution of stochastic partial differential equations (Zhang, 2001), as well as new developments in mixture coupling theories that are based on non-equilibrium thermodynamics for developing new advanced mathematical models (Chen et al., 2018a, 2018b).

The centrality of an approach that has to be based on complexity theory is in line with the recent addresses by the United Nations in the last Disaster Risk Reduction Report with respect to risk management: "*The priorities for action…spur a new understanding of risk, and the obvious value of discerning the true nature and behaviour of systems rather than a collection of discrete elements. This view allows the use of complexity theory for risk management problems…*" (UN GARDRR, 2019). It is apparent then, that the obligation of our community in dealing with thermo-chemo-hydro-geomechanical coupling, within multiscale natural systems, is on *discerning their true nature and behaviour*. It follows that we can be truly functional if we can make the COVID-19 emergency re-enter at least the edge-of-chaos, by managing quantitative approaches for both disaster risk reduction and mitigation strategy design.

An Italian case of environmental complexity: preparing for the future

The Politecnico di Bari, together with ETH Zurich, in the last years, has been addressing problems related to the treatment and reuse of highly contaminated marine sediments. The research was prompted by the huge environmental emergency at Taranto city (south of Italy), one of the most polluted sites in Europe. The national government has adopted extraordinary measures in this case, with geotechnical studies on the characterization and treatment of marine sediments representing part of these activities (Vitone et al., 2016, 2018).

If the characterization of sediments, in their current contaminated state, has demonstrated that they can represent a complex system, exhibiting long-term predictable behaviour, the data have also shown that chemo-hydro-mechanical processes can prompt chaotic behaviour in some of them (Kimura et al., 2008; Sollecito et al., 2019). This is mainly due to the random presence within the sediment matrix of some types of organic matter, diatoms, and bacteria. However, when testing stabilization and solidification (S/S) treatments, the addition of green additives, such as active carbon and biochar, for chemical remediation has shown encouraging results. In particular, biochar, which is mainly the by-product of agricultural waste pyrolysis, has been found to be a promising and cheap adsorbent material, although not affecting the binder’s mechanical performance (Federico et al., 2015; Todaro et al., 2019).

The approach to the specific contaminated Italian site is going to be carried out following what the United Nations hope when dealing with risk management (UN_GARDRR, 2019). The whole system is being considered as a complex system, which exhibits emergent properties that arise from interactions among its constituent parts, more than that of dealing with a complicated system can be (dis-)assembled and understood as the sum of its parts (Fig. 8). Facing complexity means that some uncertainties in any complex system will always remain unmeasurable. However, the risks can be characterized and quantified, to some degree, by networks made up of individual agents which interactions exert macroscopic consequences feeding back to individual behaviour. Understanding sensitivities to change and system reverberations are far more important and more challenging when dealing with complex systems. This is because, as already anticipated, changes can prompt domino-effects which can be non-linearly amplified and associated path dependencies, causing significant changes and potentially irreversible consequences which make the system enter the chaotic state.

The auspice is then to plan ahead and prepare our community for similar events in the future by thinking about disaster risk management in environmental systems as the management of complexity. It follows that, from characterization to remediation, it becomes crucial to develop a holistic understanding of a system's components and processes, including precursor signals and anomalies, systems reverberations, and sensitivities to further modifications.

The knowledge acquired in the last years related to the Taranto site has brought about the building of a Conceptual Design Site Model that includes various multidisciplinary data (chemical, geochemical, hydro-mechanical, environmental technology), and which can be used to integrate modeling for reliable predictions of the system future development (Vitone et al., 2018; Sollecito et al., 2019).

Bayesian framework to quantify uncertainty in geoenvironmental and epidemiological problems

The development of Bayesian theory as the mathematical expression of the rules of logic (Jeffreys, 1948; Cox, 1961), or according to Laplace, as the codification of *"common sense…to calculation,"* defines probability, not as the frequency of random events, but as the mapping of any logical proposition onto the interval [0, 1]. On this scale, a true statement is given the value of 1; disproval or falsehood will give it the value of 0, and all other propositions, the validity of which is uncertain because of incomplete knowledge, are ranked within [0, 1]. In that respect it provides a much broader framework to that of the "frequentist approach," not simply counting the appearance of random events, but allowing the assessment of the logical cohesion (Jaynes, 2003) of any new theory, thus being an indispensable tool for the research efforts proposed in the current article.

The basic rule of establishing the truthfulness of a logical combination AB from two independent scientific arguments A and B is that in the presence of some background information I, the plausibility of AB, P(AB|I), depends first of all on whether B is true under I, and after that that A is also true under I and B now, or in mathematics P(AB|I) = P(B|I) P(A|BI), and where the order of A and B can be reversed. The more common application of this rule consists in assessing a hypothesis H, after initial information I is supplemented by measured data D:

$$p(H \mid DI) = P(H \mid I)\, {}^{P(D \mid HI)}\!\big/_{P(D \mid I)} \tag{1}$$

Here, P(H|I) is denoted as the prior probability of H given the I (but prior to obtaining D), and P(H|DI) the posterior probability of H after both D and I. The above expression provides the mechanism to update the uncertainty assessment as new information becomes available, but also to utilize through the prior any soft or qualitative (non-numerical) information, such as the experience of engineers/scientists on a particular problem or site in the calculation of uncertainty.

Most importantly, Bayesian theory through tools, such as Eq. 1, provides the mathematics to evaluate the cohesion and consistency of logical structures, i.e., of conceptual models, such as of those discussed in section 3.1, and of others that will need to be developed to address the complexities of the current situation. In particular, for geoenvironmental and epidemiological problems where knowledge acquisition is incremental, the Bayesian approach has provided the mechanism for the update of probabilities, thus reflecting at each point the state of our knowledge.

As such Bayesian theory has a long history of application in public health and medical studies, such as for the analysis of clinical trials (for example, Etzioni and Kadane, 1995; Spiegelhalter et al., 2004; Biswas et al., 2009; Schoenfeld et al., 2009); for studies in population genetics (for example, Sorensen and Gianola, 2002; Beerli, 2006); to estimate the neurodevelopment health effects of multi-pollutant metal mixtures and the toxicological impacts of air pollutants (Bobb et al., 2015); to evaluate diagnostic protocols (Broemeling, 2007); to elucidate the operation of the central nervous system during sensorimotor learning (Kording and Wolpert, 2004), and numerous other cases.

The US Department of Health and Human Services, Food and Drug Administration, Center of Biologics Evaluation and Research in its 2010 report *"Guidance for the use of Bayesian Statistics in Medical Device Clinical Trials"* states that major advantages of the Bayesian methods constitute: (i) the use of prior information reduces the need for large sample sizes and provides more precision and flexibility in decision-making; (ii) the iterative updating capability of the Bayesian method allows for midcourse correction during a trial design, or changes in the sequence and size of trials; and (iii) it allows flexibility in cases of missing data and *"…can sometimes be used to obtain an exact analysis when the corresponding frequentist analysis is only approximate…"*

Bayesian hierarchical models were reported on March 30, 2020, as the tool used for estimation of the number of infections from SARS-CoV-2 in 11 European countries (Flaxman et al., 2020). These models are structured hierarchically, that is of a model that consists of sub-models, and which within a Bayesian framework integrates all these sub-models by accounting for their contribution to the total model uncertainty.

Bayesian methods, such as the Bayesian Maximum Entropy (BME), have found many applications in several geoenvironmental problems, which span earthquake and soil degradation (for example, Ching and Glaser, 2003; Corral, 2005), soil and rock excavation studies (for example, Gens et al., 1988; D' Or et al., 2001), risks from flooding (for example, Gelder, 1996; Solana-Ortega and Solana, 2001), incineration air pollution problems (for example, Paleologos et al., 2018), groundwater contamination problems (for example, Woodbury and Rubin, 2000; Ye et al., 2004), and environmental risk studies (Lerche and Paleologos, 2001), among others. Bayesian methods have a long record in the development of stochastic governing equations describing flow and contaminant transport in the unsaturated zone (for example, Yeh et al., 2015) and have been extensively used to assist in the analysis of aquifer data, such as from hydraulic tomography in layered heterogeneous aquifers (Li et al., 2019), of karst spring discharge (Hao et al., 2015), to infer nitrogen loadings from crop types (Ransom et al., 2018), etc. The Bayesian framework is so versatile that the same researcher can apply it to both geoenvironmental and public health problems (e.g., see Christakos and Serre, 2000; Christakos et al., 2007). Given the significance of the Bayesian approach as a tool in the geoenvironmental, vadose zone, and epidemiological studies it is expected to be contributing significantly to the common research efforts during the post-COVID-19 era.

Multidisciplinary research and leadership to counter with COVID-19

The challenges that the pandemic of COVID-19 has brought to the environmental geotechnics field are multifaceted. It is impossible to solve all problems by relying on a single discipline. Therefore, multidisciplinary research is very necessary to strengthen and enrich the outcomes of the research efforts. For instance, to solve the pathogen-soil interaction mechanism, environmental geotechnical experts need an in-depth understanding of the characteristics and properties of pathogens in-depth, which requires the help of experts in the field of pathogens. Not only that, but we also need guidance from the infectious disease field and related medical experts to establish professional laboratories that meet safety standards, to carry out collaborative tests, and take the necessary protective measures to prevent laboratory workers from being infected. If it is intended to develop high-performance remediation materials for pathogen-contaminated soils, cooperation with experts in the field of material science will enable solving such problems easier. Another example of a collaborative research is the recycling or disposal of MW which requires thorough understanding of relevant laws and regulations and consultation with a number of entities that span from environmental to public health agencies and relevant governmental departments. This is needed in order to take corrective measures during collection, sorting, transportation, storage, and disposal of solid waste and to give scientific advice on potential landfill site selection.

The speed with which medical and public health information was transferred across the world during the pandemic points out to the need, after the renormalization phase, to create new well-designed data and fast knowledge exchange platforms so that countries and scientists can share their experience. This is vital because, as it became apparent during this pandemic, decision-makers worldwide, have to rely on data analysts and mathematicians to convert complex data sets into clear arguments, which they then can use to make difficult policy decisions.

In addition to multi-disciplinary research efforts, scientists and engineers in the environmental disciplines will be called to provide their expertise in strengthening and potentially amending the environmental regulations in most countries. The emphasis on environmental laws, directives, and regulations in all countries has been until now on the protection of public health and the environment from chemical pollution. It appears with the existing pandemic some re-thinking is required to upgrade and enhance regulatory controls in order to address threats from viral and other pathogenic infections.

Immediate reductions in human activities including road traffic, air traffic, and business all around the world decreased the level of air pollution. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have recently published satellite images that captured a significant reduction in air pollution and CO_2 emissions in several countries, including China and many European cities. Further, the images from the ESA indicate sharp reductions in the level of nitrogen over France and Italy. This dramatic drop in air pollution may have been seen for the first time in the recent era. As well as possibly causing serious damage over time to the human respiratory system, air pollution can significantly hurt the quality of soil and water resources. Governments all around the world have been imposing lockdowns on human activities, which may result in further reduction of the pollution in the air, water, air, and land. It is too early to consider this as a benefit to the environment of a lasting effect. However, these changes prove that many environmental problems require international cooperation urgently, as Saadi of Shiraz (1184 – 1283) reminded us more than 700 hundred years ago that: "*Human beings are members of a whole, in the creation of one essence and soul. If one member is afflicted with pain, other members uneasy will remain*. *If you have no sympathy for human pain, the name of human you cannot retain*". A positive outcome of this epidemic might be a realization of importance of international cooperation in order to give the Earth a chance to breathe.

Finally, it is important to understand that the hopeful assumption that the COVID-19 infection will diminish and disappear during the summer is probably a misconception as there are no data to support this (Somily and BaHammam, 2020). COVID-19 is often compared with the Spanish influenza, which was caused by an H1N1 virus of avian origin (CDC, 2019). Fig. 9 (CDC, 2019; Morens and Fauci, 2007) shows that the first wave started approximately in late spring of 1918, peaking in October-November of that year, and subsiding and almost disappearing during 1919. It re-appeared forcefully in 1920 and peaked in February and March of that year, reaching 70% of the mortality of the 1918 highs, to drop for the remainder of 1920 and the majority of 1921. The Spanish influenza made a re-appearance in November of 1921 that lasted until April of 1922. About 500 million people got infected during this pandemic, a number that represented one-third of the world population at that time, with the number of deaths estimated to be at least 50 million worldwide. As a measure of comparison, this ranks lower than WW2, where the number of deaths is estimated to have exceeded 75 million people and is more than double the number of deaths caused by WW1. At present, no one knows if there will be a second or a third wave of the COVID-19 pandemic like the Spanish influenza.

It appears that both the scientific community and the political leadership in most countries, apart from a few notable exceptions, were caught unprepared to face the severity of the pandemic with countries that emulated the strict measures implemented in China to have fared better in terms of infected and mortality rates. Thus, for the future, it will be extremely instrumental to identify what leadership characteristics are critical for public officials and what public health and economic measures (and at what speed) should be considered as desirable or "best practices" to face impending massive disasters.

Conclusions

The current article focuses on the role of environmental geotechnics in dealing with the consequences of the global COVID-19 pandemic. The importance of the profession is highlighted while suggestions and different perspectives by authors around the world are combined in order to articulate ways to address the issues brought by the COVID-19 pandemic and to better help our society. Some important research topics and directions are proposed.

(1) Environmental geotechnics has long been dedicated to using multi-disciplinary perspectives, techniques, and methods to solve environmental-related geotechnical

engineering problems. In response to the geoenvironmental effects caused by COVID-19, our scientific community can apply long-term accumulated professional skills and expertise to play an irreplaceable role and make important contributions to the global fight against the current pandemic as well as future massive disasters.

(2) It is imperative for the environmental geotechnics community to perform a systematic study to reveal the mechanisms of pathogen-soil interaction and the impact on soil engineering properties. This is a fundamental step in formulating accurate environmental and geotechnical interactions.

(3) Understanding pathogen transport mechanisms and its controlling factors in the subsurface are essential for taking countermeasures for containing and remediating pathogen-contaminated sites. According to the characteristics of the SARS-CoV-2 contaminated soils or groundwater, it is necessary to develop new technologies in cooperation with other related disciplines that go beyond current in-situ isolation and remediation techniques. Biogeotechnical approaches would have potential applications and deserve more attention in the future.

(4) Environmental geotechnics researchers should work together with material scientists and engineers to develop novel and high-performance materials that will prevent the SARS-CoV-2 from entering the geoenvironment.

(5) In principle, municipal waste contaminated with the SARS-CoV-2 can be treated similarly to medical waste by sterilization and incineration. However, the amounts of waste involved, and its safe transportation, sorting, and disposal are challenging tasks for the waste management industry, particularly in less developed countries.

(6) Geotechnical and environmental scientists and engineers need to work together to develop new tools and site investigation methods for rapid and contactless deployment

in the field during emergencies, such as the COVID-19 pandemic.

(7) Development of models to simulate SARS-CoV-2 transmission in the geoenvironment with emphasis on multi-scale and non-linear dynamic descriptions of complex systems would significantly improve our predictive capabilities.

(8) The Bayesian theory is a conceptual tool that has been applied to both geoenvironmental and public health problems. It can operate as a common language during multi-disciplinary efforts linking environmental geotechnics, public health, and medical researchers.

(9) Strengthening pandemic-induced environmental risk assessment and management would benefit both in reducing risks and in developing mitigation design strategies.

(10) Because the challenges brought by COVID-19 pandemic are multifaceted, it is recommended that multidisciplinary research is pursued with several scientific fields in engineering, science, public health, and medicine in order to address the issues from a holistic approach. In addition, it is important to strengthen the coordinated action between the scientific community, regulators, political leadership, and stakeholders.

It can be concluded that the outbreak of the COVID-19 brings many new challenges to environmental geotechnics. The community must strategically plan and act on addressing these so that the lessons learned are used to prepare for similar events in the future. This requires us to be more united, inclusive, and far-sighted than ever.

Acknowledgements

The authors would like to acknowledge the insightful comments received from: Prof. Ennio Marques Palmeira, University of Brasília, Brazil; Prof. Joaquin Marti, Principia Ingenieros Consultores, Madrid, Spain; Prof. Annamaria Cividini, Politecnico di Milano, Italy; Prof. Albert T. Yeung, University of Hong Kong, Hong Kong, China; Prof. Francesco Mazzieri, Università Politecnica delle Marche, Italy; Prof. Benoît Courcelles, Polytechnique Montréal, Canada, and Prof. Leon van Paassen, Arizona State University, AZ, USA that have improved this article significantly.

References

Abarbanel H 1997 Analysis of Observed Chaotic Data Springer-Verlag New York Inc 272

An introduction to zeolite, https://kiki-health.com/an-introduction-to-zeolite/

Atkinson J, Chartier Y, Pessoa-Silva CL, et al., editors 2009 Natural Ventilation for Infection Control in Health-Care Settings. Geneva: World Health Organization; Annex C, Respiratory droplets. Available from: https://www.ncbi.nlm.nih.gov/books/NBK143281/

Artur R Nigel C 2004 Survival of human enteric viruses in the environment and food Fems Microbiology Reviews 28(4) 441 453

Baranger M 2002 Chaos, complexity, and entropy. A physics talk for non-physicists Source: necsi.org/projects/baranger/cce.pdf

Bareither CA Wolfe GL McMahon KD Benson CH 2013 Microbial diversity and dynamics during methane production from municipal solid waste Waste Management 33(10) 1982 1992.

Barlaz MA Schaefer DM Ham RK 1989 Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill Applied and Environmental Microbiology 55(1) 55 65

Beerli P 2006 Comparison of Bayesian and maximum-likelihood inference of population genetic parameters Bioinformatics 22(3) 341 345

Biswas S Liu DD Lee JJ Berry DA 2009 Bayesian clinical trials at the University of Texas M. D. Anderson Cancer Center Clinical Trials (London, England) 6(3) 205 216 DOI: 10.1177/1740774509104992

Bo MW 2011 Historical advancements of geotechnical engineering and their application in the construction industry and beyond First International Conference in Advancement in Geotechnical Engineering, Perth, Australia

Bo MW 2014 Role of Environmental Geotechnics Environmental Geotechnics, Institution of Civil Engineers (UK) 1 (EG4) 198

Bobb JF Valeri L Claus Henn B Christiani DC Wright RO Mazumdar M Godleski J Coull BA July 2015 Bayesian kernel machine regression for estimating the health effects of multi-pollutant mixtures Biostatistics 16(3) 493 508 https://doi.org/10.1093/biostatistics/kxu058

Breidablik HJ Lysebo DE Johannesse L Skare A Kleiven O Andersen JR 2020 Effects of hand disinfection with alcohol hand rub, ozonized water or soap water –time for reconsideration Journal of Hospital Infection in press

Broemeling LD 2007 Bayesian Biostatistics and Diagnostic Medicine Chapman and Hall/CRC 216 ISBN 9781584887676

Carducci A Federigi I Verani M 2013 Virus occupational exposure in solid waste processing facilities Annals of Occupational Hygiene 57(9) 1115 1127

Casanova LM Weaver SR 2015 Inactivation of an enveloped surrogate virus in human sewage Environmental Science & Technology Letters 2(3) 76 78

Cascella M, Rajnik M, Cuomo A, et al. (Updated 2020 Mar 20) Features, Evaluation and Treatment Coronavirus (COVID-19). In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2020 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK554776/

Chandana N Goli VSNS Mohammad A Singh DN 2020 Characterization and Utilization of Landfill- mined-soil-like-fractions (LFMSF) for sustainable development: A Critical appraisal. Waste and Biomass Valorization. https://link.springer.com/article/10.1007%2Fs12649-020-01052-y

Chen QL Li H Zhou X-Y Zhao Y Su J-Q Zhang X Huang F-Y 2017 An underappreciated hotspot of antibiotic resistance: the groundwater near the municipal solid waste landfill Science of the Total Environment 609 966 973

Chen X, Wang M, Hicks MA, Thomas HR 2018a A new matrix for multiphase couplings in a membrane porous medium International Journal for Numerical and Analytical Methods in Geomechanics 42(10) 1144 1153

Chen X Thornton SF Pao W 2018b Mathematical model of coupled dual chemical osmosis based on mixture-coupling theory International Journal of Engineering Science 129 145 155

Cheng L Yang Y Chu J 2019 In-situ microbially induced Ca2+-alginate polymeric sealant for seepage control in porous materials Microbial Biotechnology 12 (2) 324 333

Ching J Glaser SD 2003 Identification of soil degradation during earthquake excitations by Bayesian inference Earthquake Engineering and Structural Dynamics 32 845 869

Christakos G. Serre M.L 2000 BME analysis of spatiotemporal particulate matter distributions in North Carolina Atmospheric Environment 34(20) 3393 3406

Christakos G Olea RA Yu H-L 2007 Recent results on the spatiotemporal modeling and comparative analysis of Black Death and bubonic plague epidemics Public Health 121(9) 700 720

Chu J Stabnikov V Ivanov V 2012 Microbially induced calcium carbonate precipitation on surface or in the bulk of soil Geomicrobiology Journal 29(6) 544 549

Chu Y Jin Y Flury M Yates MV 2001 Mechanisms of virus removal during transport in unsaturated porous media Water Resources Research 37(2) 253 263

Cookson Jr JT 1969 Mechanism of virus adsorption on activated carbon Journal-American Water Works Association 61 52 56 doi:10.1002/j.1551-8833.1969.tb03702.x

Corral A 2005 Mixing of rescaled data and Bayesian inference for earthquake recurrence times

Nonlinear Processes in Geophysics 12 89 100

Cox RT 1961 The Algebra of Probable Inference John Hopkins University Press (reprint of original 1925 edition) pp. 114

Cui H Jiang J Gu W Sun C Wu D Yang T Yang G 2010 Photocatalytic inactivation efficiency of anatase nano-TiO_2 sol on the H9N2 avian influenza virus. Photochemistry and Photobiology 86(5) 1135 1139

Dare R 2000 Complexity: the Emerging Science at the Edge of Order and Chaos Research Seminar in Engineering Systems (ESD.83) Massachusetts Institute of Technology

Decrey L Kazama S Udert KM Kohn T 2015 Ammonia as an in-situ sanitizer: inactivation kinetics and mechanisms of the ssRNA virus MS2 by NH_3 Environmental Science & Technology 49(2) 1060 1067

Decrey L Kohn T 2017 Virus inactivation in stored human urine, sludge and animal manure under typical conditions of storage or mesophilic anaerobic digestion Environmental Science: Water Research & Technology 3(3) 492 501

Dejong JT DeJong JT Soga K Kavazanjian E Burns S van Paassen L Fragaszy R Al Qabany A Aydilek A Bang SS Burbank M Caslake L Chen CY Cheng X Chu J Ciurli S Fauriel S Filet AE Hamdan N Hata T Inagaki Y Jefferis S Kuo M Laloui L Larrahondo J Manning D Martinez B Mortensen B Nelson D Palomino A Renforth P Santamarina JC Seagren, EA Tanyu B Tsesarsky M Weaver T 2013 ‘Biogeochemical processes and geotechnical applications: progress, opportunities and challenges. Geotechnique 63(4) 287 301

Deng N et al. 2014 Experimental study on co-pyrolysis characteristics of typical medical waste compositions Journal of Central South University 21

D’ Or, D Bogaert P Christakos G 2001 Application of the Bayesian maximum entropy (BME) approach to soil texture mapping Stochastic Environmental Research and Risk

Assessment (SERRA) 15 87 100

Du YJ Wu J Bo Y.L., Jiang NJ 2020 Effects of acid rain on physical, mechanical and chemical properties of GGBS-MgO solidified/stabilized Pb-contaminated clayey soil. Acta Geotechnica 15(4) 923-932

Etzioni RD. Kadane JB 1995 Bayesian Statistical Methods in Public Health and Medicine Annual Review of Public Health 16 23 41

Fang S Jiang L Li P Bai J Chang C 15 March 2020 Study on pyrolysis products characteristics of medical waste and fractional condensation of the pyrolysis oil Energy 195 No. 116969

Federico A Vitone C Murianni A 2015 On the mechanical behaviour of dredged submarine clayey sediments stabilized with lime or cement Canadian Geotechnical Journal 52 1 11

Fei X Zekkos D Raskin L 2015 Archaeal community structure in leachate and municipal solid waste is correlated to the methane generation and volume reduction during biodegradation of municipal solid waste Waste Management 36 184 190

Ferreira P 2001 Tracing Complexity Theory. (on-line notes for ESD.83 - Research Seminar in Engineering Systems at MIT). http://web.mit.edu/esd.83/www/notebook/NewNotebook.htm

Flaxman S Mishra S Gandy A et al. 30 March 2020 Estimating the number of infections and the impact of non-pharmaceutical interventions on COVID-19 in 11 European Countries. Imperial College London COVID-19 Response Team pp. 35. DOI: https://doi.org/10.25561/77731. Available at: https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-Europe-estimates-and-NPI-impact-30-03-2020.pdf

Fukuzaki S 2006 Mechanisms of actions of sodium hypochlorite in cleaning and disinfection processes Biocontrol Science 11(4) 147 157.

Gallagher EM 1998 Biological clogging of geocomposites exposed to raw landfill leachate over an extended period Waste Management & Research 16(5) 421 429

Gelder PH AJM 1996 A Bayesian analysis of extreme water levels along the Dutch coast using flood historical data Stochastic Hydraulics. 7 243 251

Gens A., Ledesma A., Alonso E.E., Back analysis using prior information - Application to the staged excavation in rock. Proc. 6th Int. Conf. on Numerical Methods in Geomechanics, Innsbruck, pp.2009-2016, 1988.

Gerba CP Tamimi AH Pettigrew C Weisbrod AV Rajagopalan V 2011 Sources of microbial pathogens in municipal solid waste landfills in the United States of America. Waste Management & Research 29(8) 781 790.

Graiver DA Topliff CL Kelling CL Bartelt-Hunt SL 2009 Survival of the avian influenza virus (H6N2) after land disposal Environmental Science & Technology 43(11) 4063 4067.

Hao Y. Huo X. Duan Q *et al.* 2015 A Bayesian analysis of nonstationary generalized extreme value distribution of annual spring discharge minima Environ Earth Sci **73** 2031 2045 https://doi.org/10.1007/s12665-014-3552-7

Haque MA Chen B 2019 Research progresses on magnesium phosphate cement: A review. Construction and Building Materials 211 885 898

Harvard T.H. Chan School of Public Health 2020 Air pollution linked with higher COVID-19 death rates, https://www.hsph.harvard.edu/news/hsph-in-the-news/air-pollution-linked-with-higher-covid-19-death-rates/

Hassan IE Mohamedelhassan E Yanful Bo. MW 2016 Enhanced electrokinetic bioremediation by pH stabilisation Environmental Geotechnics Institution of Civil Engineers (UK) 5(EG4) 222 233

He J Gao Y Gu Z Chu J Wang L 2020 Characterization of crude bacterial urease for $CaCO_3$

precipitation and cementation of silty sand Journal of Materials in Civil Engineering, ASCE, 32 (5)

Heo Y Park J Lim S-I Hur H-G Kim D Park K 2010 Size-resolved culturable airborne bacteria sampled in rice field, sanitary landfill, and waste incineration sites Journal of Environmental Monitoring 12(8) 1619 1624

IDL 1997 Italian Legislative Decree n. 22, 5 February 1997, Implementation of European Directives 91/156/CEE on waste 91/689/CEE on hazardous waste and 94/62/CE on packaging and packaging waste

Jacobson KH Lee S McKenzie D Benson CH Pedersen JA 2009 Transport of the pathogenic prion protein through landfill materials Environmental Science & Technology 43(6) 2022 2028

Jaynes ET 2003 Probability Theory: The Logic of Science Cambridge University Press 758

Jeffreys H Sir 1948 Theory of Probability (International Series on Monograms in Physics) 2nd Edition. Clarendon Press, Oxford, 412 pp. (originally in 1939, later editions 1948, 1961, 1967, 1988)

Jha B, Singh DN 2016. Fly Ash Zeolites: Innovations, Applications and Directions, DOI:10.1007/978-981-10-1404-8, https://www.springer.com/gp/book/9789811014024, 191-202 pp, Springer Singapore

Jiang NJ Du YJ Liu K 2018 Durability of lightweight alkali-activated ground granulated blast furnace slag (GGBS) stabilized clayey soils subjected to sulfate attack. Applied Clay Science 161 70-75

Jiang NJ Tang CS, Hata T Courcelles B Dawoud O Singh DN 2020 Bio-mediated soil improvement: The way forward Soil Use and Management 36(2) 185 188.

Jiang NJ Tang CS Yin LY Xie YH Shi B 2019 Applicability of Microbial Calcification Method for Sandy Slope Surface Erosion Control Journal of Materials in Civil Engineering 31(11) 04019250

Johnston PM and O'Kelly BC 2016 Importance of environmental geotechnics. Environmental Geotechnics 3(6) 356 358, https://doi.org/10.1680/envgeo.13.00123

Kalwasińska A Burkowska A 2013 Municipal landfill sites as sources of microorganisms potentially pathogenic to humans Environmental Science: Processes & Impacts 15(5) 1078 1086

Kamerling JP, Gerwig GJ, 2007. Comprehenssive Glycoscience, https://www.sciencedirect.com/topics/chemistry/glycoprotein

Katan J 2017 Diseases caused by soilborne pathogens: biology, management and challenges Journal of Plant Pathology 99(2) 305 315

Kiki Health 2019 An introduction to zeolite: what is zeolite? https://kiki-health.com/an-introduction-to-zeolite/

Kimura M Jia ZJ Nakayama N Asakawa S 2008 Ecology of viruses in soils: Past, present and future perspectives Soil Science & Plant Nutrition 54 1-32

Khatami HR O'Kelly BC 2013 Improving mechanical properties of sand using biopolymers Journal of Geotechnical and Geoenvironmental Engineering 139(8) 1402 1406, https://doi.org/10.1061/(ASCE)GT.1943-5606.0000861

Kording KP. Wolpert DM 2004 Bayesian integration in sensorimotor learning Nature 427 244 247

Kraljević Pavelić S Simović Medica J Gumbarević D Filošević A Pržulj N Pavelić K 2018 Critical review on zeolite clinoptilolite safety and medical applications *in vivo*. Frontiers in Pharmacology 9 1350. https://doi.org/10.3389/fphar.2018.01350

Lerche I Paleologos EK 2001 Environmental Risk Analysis McGraw-Hill**,** Professional

Engineering Series 436 ISBN: 0-07-137266-0

Li K Zhang Y Yeh T-C J Zhao L Su X Wang YL Qi Y 2019 An iterative scheme to map and incorporate geologic information of discontinuous heterogeneity in hydraulic tomography Jour of Hydrology 579 [124143] https://doi.org/10.1016/j.jhydrol.2019.124143

Lorenz EN 1963 Deterministic nonperiodic flow Journal of the Atmospheric Sciences 20 130 141

Makarichi L Jutidamrongphan W Techato K 2018 The evolution of waste-to-energy incineration: a review Renewable and Sustainable Energy Reviews 91

Malham SK Rajko-Nenow P Howlett E Tuson K E Perkins TL Pallett DW Wang H Jago CF Jones DL McDonald JE 2014 The interaction of human microbial pathogens, particulate material and nutrients in estuarine environments and their impacts on recreational and shellfish waters Environmental Science-Processes & Impacts 16(9) 2145 2155

Mao K Zhang H Yang Z 2020 Can a paper-based device trace COVID-19 sources with wastewater-based epidemiology? Environ. Science & Technology DOI: 10.1021/acs.est.0c01174

Matsumoto T Sunada K Nagai T Isobe T Matsushita S Ishiguro H Nakajima A 2019 Preparation of hydrophobic La2Mo2O9 ceramics with antibacterial and antiviral properties. Journal of Hazardous Materials 378 120610

Mazurkow JM Yüzbasi NS Domagala KW Pfeiffer S Kata D Graule T 2020 Nano-sized copper (oxide) on alumina granules for water filtration: effect of copper oxidation state on virus removal performance Environ. Sci. Technol 54 1214 1222

McDougall J 2007 A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste Computers and Geotechnics 34(4) 229 246

MedicineNet 2020 Coronavirus isn’t even ‘alive’, but experts explain how it can harm, dated 26 March, 2020 https://www.medicinenet.com/script/main/art.asp?articlekey=229387

MEEC (Ministry of Ecology and Environment P.R. China) 2003 Technical Codes of Medical Wastes Centralized Disposal

MEEC (Ministry of Ecology and Environment P.R. China) 2006 Technical Specifications for Steam-based Centralized Treatment Engineering on Medical Waste

MEEC (Ministry of Ecology and Environment P.R. China) 2020 Disposal Management and Technical Guide of Emergent COVID-19 Medical Waste

Mechref Y., Novotny MV, 2007. Capillary Electrophoresis | Glycoproteins. In Encyclopedia of Separation Science https://www.sciencedirect.com/topics/chemistry/glycoprotein

Meynet P Hale SE Davenport RJ Cornelissen G Breedveld GD Werner D 2012 Effect of Activated Carbon Amendment on Bacterial Community Structure and Functions in a PAH Impacted Urban Soil Environ Sci Technol 46(9) 5057 5066

Mitchell JK Santamarina JC 2005 Biological considerations in geotechnical engineering Journal of Geotechnical and Geoenvironmental Engineering 131(10) 1222 1233

Mohamed A-MO Paleologos EK 2017 Foundations of Geoenvironmental Engineering Elsevier Butterworth-Heinemann**,** ISBN: 978-0-12-804830-6, 708

Morens DM Fauci AS 2007 The 1918 Influenza pandemic: insights for the 21st century Journal of Infectious Diseases 195 1018 1028 DOI: 10.1086/511989

Moriarty LF 2020 Public Health Responses to COVID-19 Outbreaks on Cruise Ships—Worldwide, February–March 2020 *MMWR. Morbidity and Mortality Weekly Report,* 69

Natural Therapy Pages. 2008. What are activated Liquid Zeolites, https://www.naturaltherapypages.com.au/article/zeolite, accessed on 13 April 2020.

O'Kelly BC Brinkgreve RBJ Sivakumar V 2014 Pullout resistance of granular anchors in clay for undrained condition. Soils and Foundations 54(6) 1145 1158, https://doi.org/10.1016/j.sandf.2014.11.009

Paleologos EK Elhakeem M El Amrousi M 2018 Bayesian analysis of air emission violations from waste incineration and co-incineration plants Jour. Risk Analysis 38(11) 2368 2378 DOI:10.1111/risa.13130

Palmeira EM Remigio AFN Ramos MLG Bernardes RS 2008 A study on biological clogging of nonwoven geotextiles under leachate flow Geotextiles and Geomembranes 26(3) 205 219

Qiao F Chau CK Li Z 2010 Property evaluation of magnesium phosphate cement mortar as patch repair material Construction and Building Materials 24(5) 695 700

Quanrud DM Carroll SM Gerba CP Arnold RG 2003 Virus removal during simulated soil-aquifer treatment Water Res 37(4) 753 762

Ransom KM Bell AM Barber QE Kourakos G Harter T 2018 A Bayesian approach to infer nitrogen loading rates from crop and land-use types surrounding private wells in the Central Valley, California Hydrol. Earth Syst. Sci. 22 2739 2758 doi:10.5194/hess-22-2739-2018

Rao DLN Giller KE Yeo AR Flowers TJ 2002 The effects of salinity and sodicity upon nodulation and nitrogen fixation in chickpea (Cicer arietinum). Annals of botany 89 563 570.

Reinhart DR Townsend TG 1998 Landfill Bioreactor Design and Operation Lewis Publishers Boca Raton, FL

Rowe RK Quiley RM Brachman RWI Booker JR 2004 Barrier System for Waste Disposal Facilties CRC Press London

Sasidharan S Torkzaban S Bradford SA Kookana RS Page Peter DW Cook G 2016 Transport and retention of bacteria and viruses in biochar-amended sand The Science of the total environment 548 100 109

Schoenfeld DA Zheng H Finkelstein DM 2009 Bayesian design using adult data to augment pediatric trials Clinical trials (London, England) *6*(4) 297 304 https://doi.org/10.1177/1740774509339238

Scudamore JM Trevelyan GM Tas MV Varley EM Hickman GAW 2002 Carcass disposal: Lessons from Great Britain following the foot and mouth disease outbreaks of 2001 Revue Scientifique et Technique (International Office of Epizootics) 21 (3) 775 787

Sharma S and Singh DN 2015 Characterization of Sediments for sustainable development: State of the art. Marine Georesources and Geotechnology 33(5) 447 465

Shen L Zhao B Zhang J Chen J Zhang H 2010 Virus adsorption onto nano-sized iron oxides as affected by different background solutions Chinese Journal of Environmental Science 31(4) 983 989

Silva S Palmeira EM 2019 Leachate pre-treatment using non-woven geotextile filters Environmental Geotechnics 6(1) 34 46 Doi/10.1680/jenge.16.00021

Sivakumar V O'Kelly BC Madhav MR Moorhead C Rankin B 2013 Granular anchors under vertical loading/axial pull Canadian Geotechnical Journal 50(2) 123 132 https://doi.org/10.1139/cgj-2012-0203

Solana-Ortega A Solana V 2001 Entropy-based inference of simple physical models for regional flood analysis Stochastic Environmental Research and Risk Assessment (SERRA) 15 415 446

Sollecito F Vitone C Miccoli D Plötze M Puzrin AM Cotecchia F 2019 Marine Sediments from a Contaminated Site: Geotechnical Properties and Chemo-Mechanical Coupling

Processes Geosciences 9(8) 333

Somily AM and BaHammam AS 2020 Coronavirus Disease-19 (severe acute respiratory syndrome-coronavirus-2) is not just simple influenza: what have we learned so far? Journal of Nature and Science of Medicine DOI: 10.4103/JNSM.JNSM_22_20

Song L Li L Yang S Lan J He H McElmurry SP Zhao Y 2016 Sulfamethoxazole, tetracycline and oxytetracycline and related antibiotic resistance genes in a large-scale landfill, China Science of the Total Environment 551 9 15

Sorensen D Gianola D 2002 Likelihood, Bayesian and MCMC Methods in Quantitative Genetics Springer: Statistics for Biology and Health 760

Spiegelhalter DJ Abrams K R Myles JP 2004 Bayesian Approaches to Clinical Trials and Health-Care Evaluation New York: Wiley. DOI:10.1002/0470092602

Stabnikov V Chu J Myo AN Ivanov V 2013 Immobilization of sand dust and associated pollutants using bioaggregation Water, Air, & Soil Pollution 224 1631 doi.org/10.1007/s11270-013-1631-0

Staley BF. Francis L Barlaz MA 2011 Effect of spatial differences in microbial activity, pH, and substrate levels on methanogenesis initiation in refuse Applied Environmental Microbiology 77(7) 2381 2391.

Steen WE Su-Ling BM 2015 Medical waste management - a review J Environ Manag 163

Sunada K Minoshima M Hashimoto K 2012 Highly efficient antiviral and antibacterial activities of solid-state cuprous compounds Journal of Hazardous Materials 235 265 -270

Tang CS Yin LY Jiang NJ Zhu C Zeng H Li H Shi B 2020 Factors affecting the performance of microbial‐induced carbonate precipitation (MICP) treated soil: a review Environmental Earth Sciences 79:94 doi.org/10.1007/s12665-020-8840-9

Todaro F Vitone C Notarnicola M 2019 Stabilization and recycling of contaminated marine sediments E3S Web of Conferences 92 11004

United Nations, Global Assessment Report for Disaster Risk Reduction (UN_GARDRR) 2019. https://gar.undrr.org/sites/default/files/reports/2019-05/full_gar_report.pdf

US CDC (US Centers for Disease Control and Prevention) 2019 1918 Pandemic (H1N1 virus) https://www.cdc.gov/flu/pandemic-resources/1918-pandemic-h1n1.html

US National Academies 1994 Alternatives for Groundwater Cleanup Committee on Ground Water Cleanup Alternatives, National Research Council 336 ISBN: 0-309-58624-0

van Doremalen N Bushmaker T Morris DH Holbrook MG Gamble A Williamson BN Tamin A Harcourt JL Thornburg NJ Gerber SI 2020 Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1 New England Journal of Medicine

Vaverkova MD Adamcova D Winkler J Koda E Cervenkova J Podlasek A 2019 Influence of a municipal solid waste landfill on the surrounding environment: landfill vegetation as a potential risk of allergenic pollen Int. J. Environ. Res. Public Health 16 5064 doi:10.3390/ijerph16245064

Verma S Bednar V Blount A Hogue BG (Apr 2006) Identification of Functionally Important Negatively Charged Residues in the Carboxy End of Mouse Hepatitis Coronavirus A59 Nucleocapsid Protein Jour Virology 80 (9) 4344 4355; DOI**:** 10.1128/JVI.80.9.4344-435 5.2006

Vitone C 2019 Contaminated soils and remedial strategies: geotechnical systems between complexity, chaos and sustainability Environmental Geotechnics 6(7) 431 433

Vitone C Cotecchia F Federico A Viggiani G 2018 On the geomechanical characterisation of complexities in clays: Experimental studies Italian Geotechnical Journal 2 1 29

Vitone C Federico A Puzrin AM Ploetze M Carrassi E Todaro F 2016 On the geotechnical characterisation of the polluted submarine sediments from Taranto Environmental

Science and Pollution Research 23(3) 12535 12553

Waldrop MM 1992 Complexity: the Emerging Science at the Edge of Order and Chaos. Touchstone, New York

Wang Y Wang HS Tang CS Gu K Shi B 2019 Remediation of heavy-metal-contaminated soils by biochar: a review Environmental Geotechnics https://doi.org/10.1680/jenge.18.00091

Wang YF Zhu HM Jiang XG 2018 Research situation and development of co-processing of hazardous waste in cement kiln Environmental Pollution & Control 40(8) 943 949

Weaver JE Wang L Francis L Barlaz MA 2019 Understanding Terrestrial Microbial Communities, pp. 129-150, Springer

WebMD Corona virus outbreak 2020, https://www.webmd.com/lung/what-does-covid-do-to-your-lungs

WHO (World Health Organization) 2020a Coronavirus Disease (COVID-2019) Situation Report-73, Dated: 2 April 2020, https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200402-sitrep-73-covid-19.pdf?sfvrsn=5ae25bc7_2

WHO (World Health Organization) 2020b Global Research on Coronavirus Disease (COVID-19) https://www.who.int/emergencies/diseases/novel-coronavirus-2019/global-research-on-novel-coronavirus-2019-ncov

Wigginton KR Ye Y Ellenberg RM 2015 Emerging investigators series: the source and fate of pandemic viruses in the urban water cycle. Environmental Science: Water Research & Technology 1(6) 735 746

Woodbury AD Rubin Y 2000 A full-Bayesian approach to parameter inference from tracer travel time moments and investigation of scale effects at the Cape Cod experimental site Water Resources Research 36(1) 159 171

Wu D Huang X-H Sun J-Z Graham DW Xie B 2017 Antibiotic resistance genes and associated microbial community conditions in aging landfill systems Environmental Science & Technology 51(21) 12859 12867

Wu HL Du YJ Yu J Yang YL Li VC 2020 Hydraulic conductivity and self-healing performance of engineered cementitious composites exposed to acid mine drainage. Science of the Total Environment 716 137095.

Wu HL Jin F Bo YL Du YJ Zheng JX 2018 Leaching and microstructural properties of lead contaminated kaolin stabilized by GGBS-MgO in semi-dynamic leaching tests. Construction and Building Materials 172 626-634

Xia WY Du YJ Li FS Li CP Yan XL Arulrajah A Wang F Song DJ 2019a In-situ solidification/stabilization of heavy metals contaminated site soil using a dry jet mixing method and new hydroxyapatite based binder. Journal of Hazardous Materials 369 353–361.

Xia WY Du YJ Li FS Guo GL Yan XL Li CP Arulrajah A Wang F Wang S 2019b Field evaluation of a new hydroxyapatite based binder for ex-situ solidification/stabilization of a heavy metal contaminated site soil around a Pb-Zn smelter. Construction and Building Materials 210 278–288.

Xiao B Zhao Y 2006 A review on the migration of viruses in soil and groundwater Chinese Journal of Soil Science 1 179 185

Xu K Cai H Shen Y Ni Q Chen Y Hu S Li J Wang H Yu L Huang H 2020 Management of corona virus disease-19 (COVID-19): the Zhejiang experience. Zhejiang da xue xue bao. Yi xue ban= Journal of Zhejiang University. Medical sciences 49 0-0

Yang YL Reddy KR Du YJ Fan RD 2018 Short-term hydraulic conductivity and consolidation properties of soil-bentonite backfills exposed to CCR-impacted groundwater ASCE Journal of Geotechnical and Geoenvironmental Engineering 144(6) 48-55

Ye M Neuman SP Meyer PD 2004 Maximum likelihood Bayesian averaging of spatial variability models in unsaturated fractured tuff Water Resources Research 40 W05113

Yeh T-C J Khaleel R Carroll KC 2015 *Flow Through Heterogeneous Geologic Media* Cambridge University Press. https://doi.org/10.1017/CBO9781139879323

Yu Z He P Shao L Zhang H Lü F 2016 Co-occurrence of mobile genetic elements and antibiotic resistance genes in municipal solid waste landfill leachates: a preliminary insight into the role of landfill age Water Research 106 583 592

Yu S Wang X Chen Z Wang J Wang S Hayat T Wang X 2017 Layered double hydroxide intercalated with aromatic acid anions for the efficient capture of aniline from aqueous solution Journal of Hazardous Materials 321 111 120

Zhang D 2001 Stochastic Methods for Flow in Porous Media: Coping with Uncertainties Academic Press 368

Zhang H Nordin N A Olson MS 2013 Evaluating the Effects of Variable Water Chemistry on Bacterial Transport during Infiltration. Journal of Contaminant Hydrology 150, 54–64

Zhang P Wang K Li Q Wang J Ling Y 2020.Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders-a review Journal of Cleaner Production, 258 120896

Zhan S Yang Y Shen Z Shan J Li Y Yang S Zhu D 2014 Efficient removal of pathogenic bacteria and viruses by multifunctional amine-modified magnetic nanoparticles. Journal of Hazardous Materials 274 115 123

Zhao B 2006 Transport of viruses in soil: an overview Acta Pedologica Sinica 43(2) 306 313

Figure 1. Migration trajectory and human exposure risk point of COVID-19 in water environment system (modified from Wigginton et al. (2015))

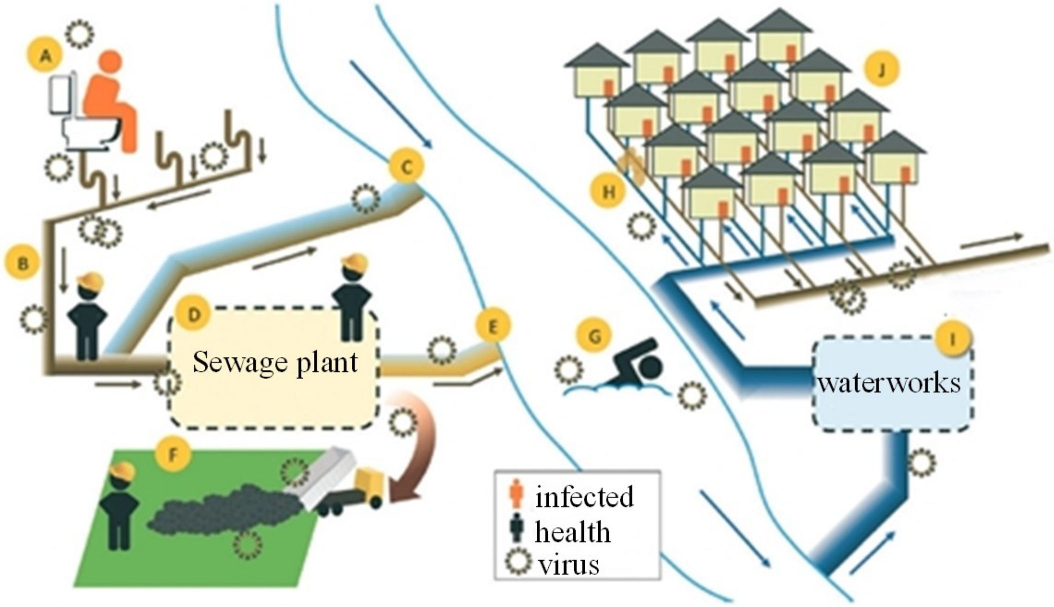

Figure 2. Essential infrastructure identified after COVID-19

Figure 3. Geo-Env-Mobility measuring and monitoring (GEM3) mobile station for rapid geotechnical, environmental, and traffic monitoring and testing developed at Nanyang Technological University, Singapore

Figure 4. (a) Bricks made by mixing melt plastic with sand and marine clay; (b) Unconfined compressive strength of gravel, sand or marine clay mixed with melt plastic

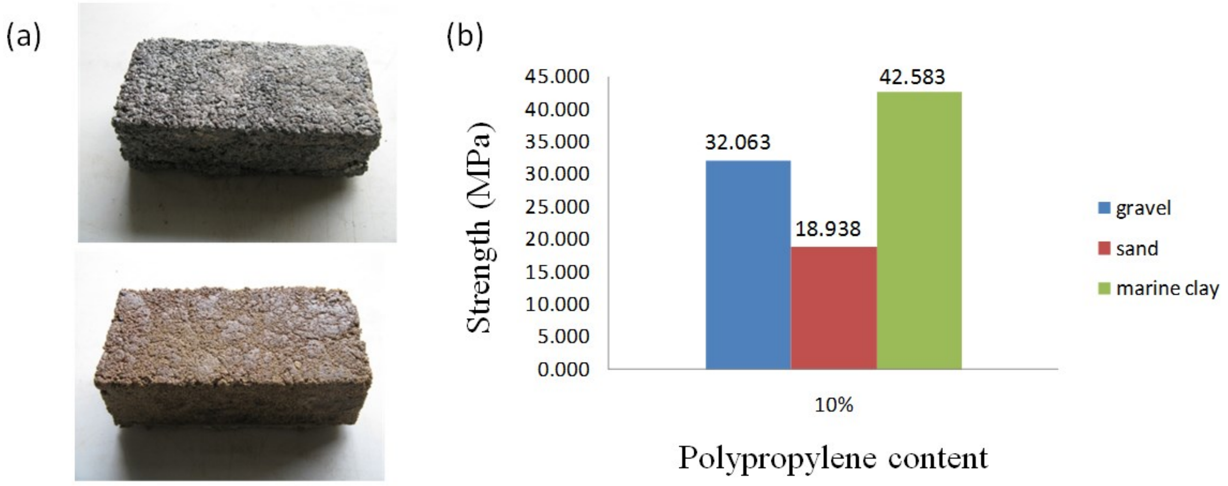

Figure 5. Scanning electron microscope image of SARS-COV-2 or 2019-nCoV (colored in yellow), the virus that causes COVID-19—isolated from a patient in the U.S., emerging from the surface of cells (blue/pink) cultured in the lab (NIH (US National Institutes of Health), March 17, 2020: https://www.nih.gov/news-events/news-releases/new-coronavirus-stable-hours-surfaces)

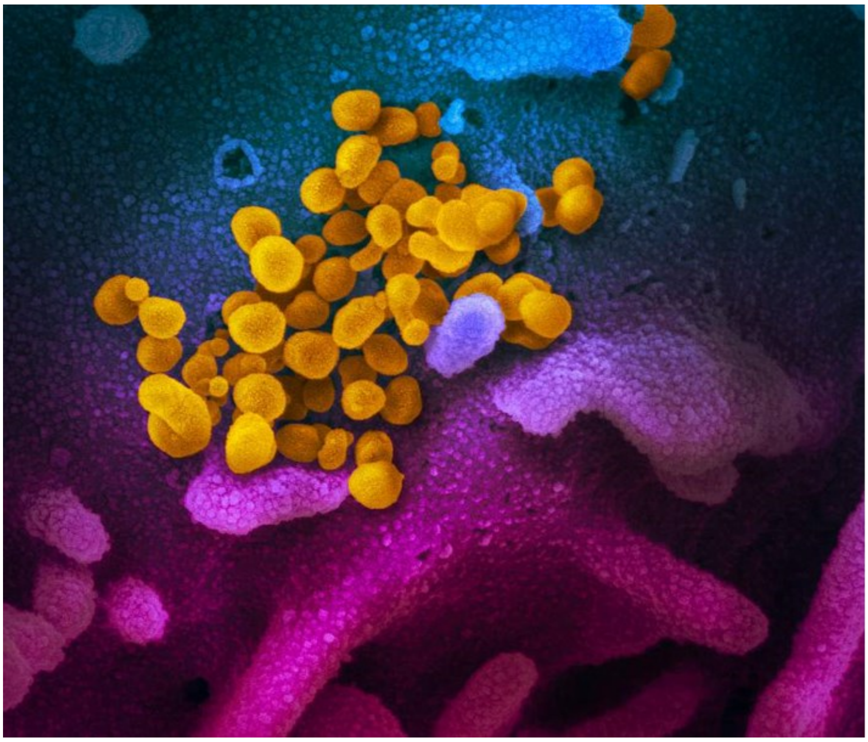

Figure 6. A pictorial model for absorption of the virus in water droplets, by the zeolite during detoxification. Top image: Zeolite, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6277462/. Bottom image: Cluster of SARS-COV-2, US National Institute of Allergy and Infectious Diseases: https://www.niaid.nih.gov/news-events/novel-coronavirus-sarscov2-images, February 13, 2020)

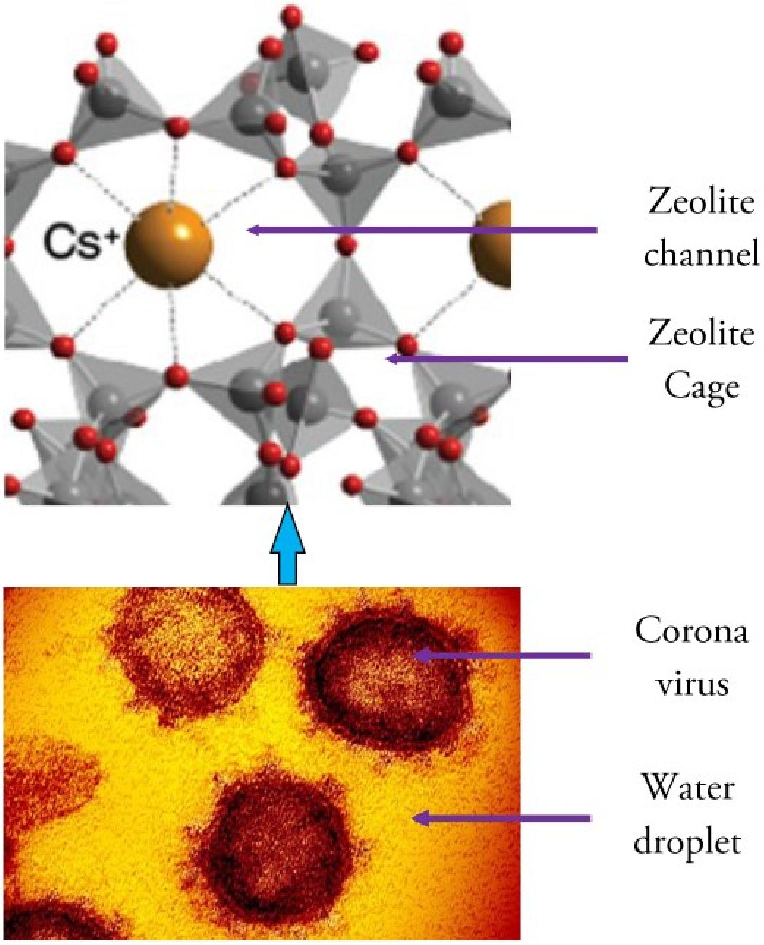

Figure 7. Characteristics of complex systems, from complexity to chaos (Ferreira, 2001)

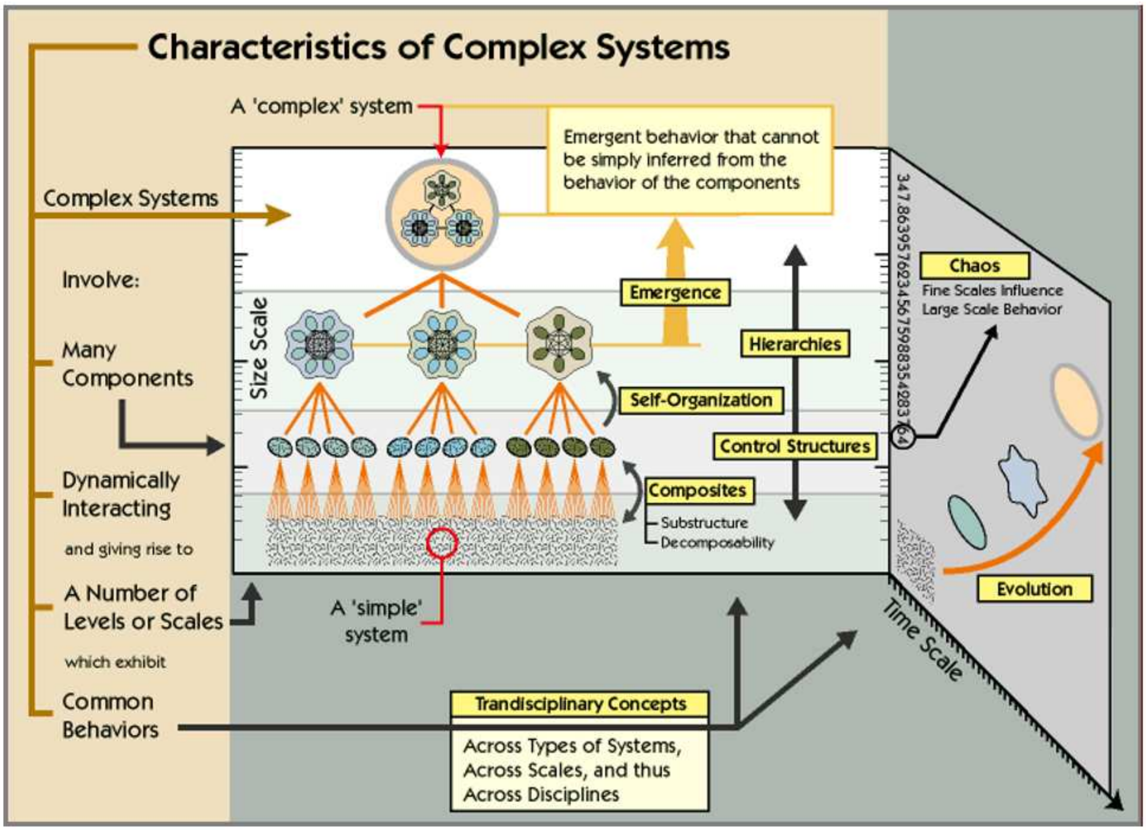

Figure 8. Complicated and complex systems (adopted from UN_GARDRR 2019)

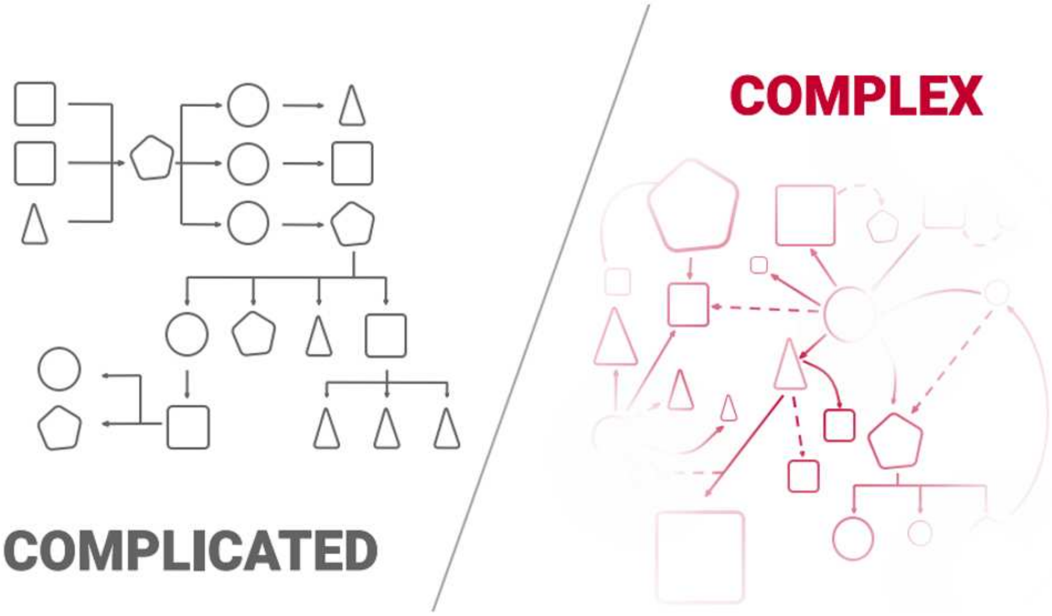

Figure 9. Monthly influenza-associated mortality in Breslau, Silesia (now Wroclaw, Poland), from June 1918 through December 1922. (CDC 2019; Morens and Fauci, 2007)