# Environmental geotechnics: Challenges and opportunities in the post-Covid-19 world

*Original*
Environmental geotechnics: Challenges and opportunities in the post-Covid-19 world / Tang, C. -S.; Paleologos, E. K.; Vitone, C.; Du, Y. -J.; Li, J. -S.; Jiang, N. -J.; Deng, Y. -F.; Chu, J.; Shen, Z.; Koda, E.; Dominijanni, A.; Fei, X.; Vaverkova, M. D.; Osinski, P.; Chen, X.; Asadi, A.; Takeuchi, M. R. H.; Bo, M. W.; Abuel-Naga, H.; Leong, E. -C.; Farid, A.; Baser, T.; O'Kelly, B. C.; Jha, B.; Goli, V. S. N. S.; Singh, D. N.. - In: ENVIRONMENTAL GEOTECHNICS. - ISSN 2051-803X. - STAMPA. - 8:3(2021), pp. 172-192. [10.1680/jenge.20.00054]

*Publisher:*
ICE Publishing

*Published*
DOI:10.1680/jenge.20.00054

**Cite this article**
Tang CS, Paleologos EK, Vitone YJ *et al*. (2021)
Environmental geotechnics: challenges and opportunities in the post-Covid-19 world.
*Environmental Geotechnics* **8(3)**: 172–192,
https://doi.org/10.1680/jenge.20.00054

**Research Article**
**Paper 2000054**
Received 18/04/2020; Accepted 27/04/2020
Published online 02/10/2020

**Keywords:** contaminated material/land contamination/waste management & disposal

**Environmental Geotechnics**

ICE Publishing

# Environmental geotechnics: challenges and opportunities in the post-Covid-19 world

**Chao-Sheng Tang**
School of Earth Sciences and Engineering, Nanjing University, Nanjing, China (Orcid:0000-0002-6419-6116) (corresponding author: tangchaosheng@nju.edu.cn)

**Evan K. Paleologos**
Department of Civil Engineering, Abu Dhabi University, Abu Dhabi, UAE

**Claudia Vitone**
Department of Civil, Environmental, Land, Building Engineering and Chemistry, Politecnico di Bari, Bari, Italy

**Yan-Jun Du**
Institute of Geotechnical Engineering, School of Transportation, Southeast University, Nanjing, China

**Jiang-Shan Li**
State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China

**Ning-Jun Jiang**
Department of Civil and Environmental Engineering, University of Hawai'i at Mānoa, Honolulu, HI, USA

**Yong-Feng Deng**
Institute of Geotechnical Engineering, School of Transportation, Southeast University, Nanjing, China

**Jian Chu**
School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

**Zhengtao Shen**
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada

**Eugeniusz Koda**
Institute of Civil Engineering, Warsaw University of Life Sciences, Warsaw, Poland

**Andrea Dominijanni**
Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy

**Xunchang Fei**
School of Civil and Environmental Engineering, Nanyang Technological University, Singapore; Residues and Resource Reclamation Centre, Nanyang Environment and Water Research Institute, Singapore

**Magdalena Daria Vaverková**
Institute of Civil Engineering, Warsaw University of Life Sciences, Warsaw, Poland; Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic

**Piotr Osiński**
Institute of Civil Engineering, Warsaw University of Life Sciences, Warsaw, Poland

**Xiaohui Chen**
School of Civil Engineering, University of Leeds, Leeds, UK

**Afshin Asadi**
Civil Engineering Discipline, International College of Auckland, Auckland, New Zealand

**Maria R. H. Takeuchi**
Graduate School of Energy Science, Kyoto University, Kyoto, Japan

**Myint Win Bo**
Bo & Associates Inc., Mississauga, ON, Canada

**Hossam Abuel-Naga**
School of Engineering and Mathematical Sciences, La Trobe University, Melbourne, Australia

**Eng-Choon Leong**
School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

**Arvin Farid**
Civil Engineering, Boise State University, Boise, ID, USA

**Tugce Baser**
Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

**Brendan C. O'Kelly**
Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland

**Bhagwanjee Jha**
Department of Civil Engineering, Dr Babasaheb Bhimrao Ambedkar Government Polytechnic, Silvassa, India

**Venkata Siva Naga Sai Goli**
Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India

**Devendra N. Singh**
Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India

**The outbreak of the coronavirus disease 2019 (Covid-19) pandemic not only has created a health crisis across the world but is also expected to impact negatively the global economy and societies at a scale that is maybe larger than that of the 2008 financial crisis. Simultaneously, it has inevitably exerted many negative consequences on the geoenvironment on which human beings depend. The current paper articulates the role of environmental geotechnics in elucidating and mitigating the effects of the current pandemic. It is the belief of all authors that the Covid-19 pandemic presents not only significant challenges but also opportunities for the development of the environmental geotechnics field. This discipline should make full use of geoenvironmental researchers' and engineers' professional skills and expertise to look for development opportunities from this crisis, to highlight the irreplaceable position of the discipline in the global fight against pandemics and to contribute to the health and prosperity of communities, to serve humankind better. In order to reach this goal while taking into account the specificity of severe acute respiratory syndrome coronavirus 2 (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 infrastructures; pandemic-induced environmental risk management; and modelling of 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 co-operation 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 3.7 million people, as confirmed by the World Health Organization (WHO) on 9 May 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 travelling and participating in social activities. The daily lives of billions of people have been disrupted with half the world under stay-home orders (*New York Times*, 3 April 2020), and the global economy is expected to suffer historic losses.

On the other hand, this pandemic has also brought a first-time realisation that the common fate of people can be secured only by coordinated global action, which has quickly been followed by acts of allegiance among countries (WHO, 2020b). Scientific collaboration and knowledge transmission have proceeded during these weeks with unmatched speed, where health officials in a European country, such as Greece, may be quoting the preliminary results announced a few hours earlier by the Chinese Academy of Sciences (iefimerida, 2020), or comparing in real time their public health measures with 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 in assessing the lessons learned from this traumatic experience when it is over.

The objective of the current paper 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 paper 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 multidisciplinary perspectives, techniques and methods to solve environmentally related geotechnical engineering problems. Its 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, geoenvironmental researchers and engineers have turned to themselves and asked, ‘How can our discipline better serve our society, fulfil 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 paper believe that environmental geotechnics should strengthen research in the following areas: pathogen–soil interactions and pathogen migration, diffusion mechanisms in soil pores and effects on soil engineering properties; in situ isolation and remediation technologies for pathogen-contaminated sites; development of new materials for rapid disinfection of pathogen-contaminated soil; and recycling and safe disposal of medical solid wastes. Effort should be devoted to international co-operation and interdisciplinary research, such as cross-disciplinary research in environmental geotechnics, public health, microbiology, medicine and other related disciplines. Particularly in the area of cross-disciplinary research, the characteristic of environmental and geotechnical problems of exhibiting large temporal and spatial uncertainties has led to the development of new techniques for quantifying uncertainty and the refinement of existing ones. Bayesian probabilistic models are particularly suitable for geoenvironmental analyses with their capability to make use of soft information and to incorporate and update new knowledge subsequently 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 modelling of pathogen transport in the geoenvironment are important research topics. Concentrated, coordinated and co-operative research efforts on these areas will provide new perspectives that will contribute to the welfare of the society, counter the multifaceted 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 to 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 remains largely unknown how pathogens interact with the geoenvironment from an engineering perspective. Soils are 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 – for example, antibiotics and medications. The 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.

(*a*) 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 of 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 labour intensive and not able to detect non-cultivable cells. Unlike culture-based methods, molecular-based methods detect specific deoxyribonucleic acid segments of the pathogen genome, which provides high specificity and accuracy. Polymerase chain reaction 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, the 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.

(*b*) Antibiotic resistance of pathogens and its implication for the geoenvironment. 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, in particular 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, waste water plants and farms have resulted in a significant increase in the 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.

(*c*) Modification of soil engineering properties by pathogens. Many microbes in nature have been found to be capable of altering soil physico-chemical properties. For example, ureolytic bacteria, such as *Sporosarcina pasteurii*, are able to hydrolyse urea and induce calcite precipitation in soil pores to improve the strength of sandy soils (Jiang *et al*., 2019, 2020). Nevertheless, there has been limited research on how pathogens could potentially alter the engineering performance of soils. Pathogenic bacteria and fungi are likely to change the physico-chemical properties of soil through their own metabolic activities (forming extracellular polymeric substances, generating gas, changing the redox environment, altering the ambient acidity–alkalinity condition etc.). These will, in turn, affect the mechanical, hydraulic and/or physico-chemical behaviour 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 that 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 and so on by changing their physiological behaviour. This is a new frontline area that deserves exploration by the geoenvironmental community.

(*d*) Soil erosion and dust control. As pathogenic microbes can stick to surfaces and be 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 (HSPH, 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 studies need to be conducted in order to develop easily applied methods of 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 (Cheng *et al*., 2019; He *et al*., 2020; Khatami and O'Kelly, 2013).

(*e*) Learning from municipal solid waste (MSW) studies. MSW and soil share many common characteristics. For instance, both are multiphase geomaterials with solid skeletons and have intermixed liquid and gas phases. Microorganisms are almost omnipresent in soils (Mitchell and Santamarina, 2005), and 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 the 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, the authors would like to highlight some (non-exhaustive) relevant studies that stem from MSW research as follows:

(*i*) characterisation methods for microbial communities in MSW and leachate (Bareither *et al*., 2013; Fei *et al*., 2015; Staley *et al*., 2011)
(*ii*) modelling long-term biochemical and other associated processes in MSW landfills (Gawande *et al*., 2010; McDougall, 2007)
(*iii*) 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)
(*iv*) airborne microorganisms in and adjacent to landfills (Heo *et al*., 2010; Kalwasińska and Burkowska, 2013)
(*v*) interactions between microorganisms and geosynthetics that are used as a containment system (Gallagher, 1998; Palmeira *et al*., 2008)
(*vi*) existence, transport and fate of pathogenic prion protein (Jacobson *et al*., 2009) and avian influenza virus (AIV) (Graiver *et al*., 2009) in landfill systems
(*vii*) 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 waste water 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). The transport of pathogens in soils can be modelled using a modified advection–dispersion theory with consideration of the die-off rate of pathogens, whereas the mass transfer of pathogens between solid and aqueous phases in soils can be modelled by a first-order attachment/detachment equation (Morales *et al*., 2014; Zhang *et al*., 2013). Organic matter in soils has been found to favour the adsorption of bacteria onto soils. In contrast, the presence of soil organic matter decreases the adsorption of viruses. The presence of clays, haematite and magnetite increases virus retention (Bitton and Harvey, 1992).

The 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' (Xiao and Zhao, 2006; 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 and 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 treatments for soils with a relatively weak purification ability, so as to prevent the virus from breaking through the soil purification barrier and further contaminating 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 Figure 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 waste water, and containers, for temporally storing pathogen-laden waste water. Potential leakage of such buried pipes and containers may result in the contamination of soils and groundwater. Installation of barriers including high-density polyethylene 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 waste water in soils and reduce the environmental impact on groundwater quality. A GM/GCL composite liner is much more effective than a GM/CCL composite liner in mitigating

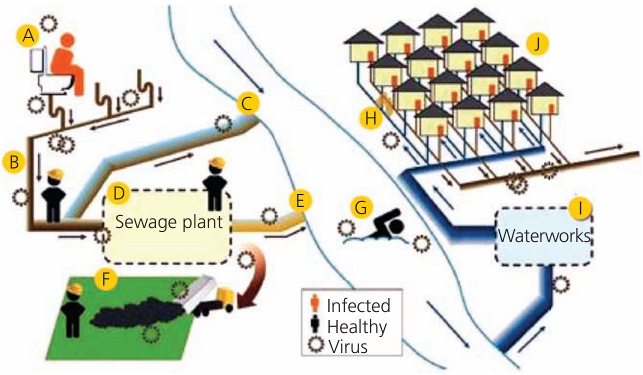


**Figure 1.** Migration trajectory and human exposure risk point of Covid-19 in the water environment system (modified from Wigginton *et al*. (2015)). A, faeces; B, municipal drainage pipe network; C, sewage outlet; D, sewage plant; E, tailwater outlet; F, sludge disposal; G, receiving water body; H, sewage pipe leakage; I, waterworks; J, user

leakage through defects in GMs (Rowe *et al.*, 2004). Vertical barriers, such as soil–bentonite slurry trench walls, overlapped deep mixed columns or GM/GCL composite walls, may be needed to contain the 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, limited studies have systematically investigated the following issues.

- Can the hydraulic conductivity of underground barrier systems be altered by permeation with pathogen-laden waste water?
- What will be the durability and service life of GMs that are exposed to pathogen-laden or sanitiser-laden waste water?
- How can transport parameters, die-off rates and mass transfer between the solid and aqueous phases of the pathogenic bacterium through GM, GCLs and CCLs be determined?
- 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 waste water containing soap, as soap is found to be able to reduce soil surface tension and may enhance the transport of waste water 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 waste water is found to exceed commonly accepted limits (Yang *et al.*, 2018), and the die-off rate of the pathogen in GCLs or CCLs is of concern. To obtain the transport parameters and die-off rates of pathogens, in particular those 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 professionals may also be needed to ensure the legitimacy of certain laboratory experiments.

## Remediation

### 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 viruses in sterilising media is obviously lower than that in non-sterilising media (Rzezutka and Cook, 2004). Quanrud *et al.* (2003) elucidated that a possible mechanism for microbe-mediated virus attenuation is the excretion of soluble microbial products, which can degrade virions and utilise 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 the aforementioned microorganisms must be closely related to the characteristics of SARS-CoV-2, and the selection of or injection of microorganisms to contaminated soils requires a joint effort from virology researchers.

By introducing or activating 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 virus in the soil and reduce the pollution range, particularly when the mineralised products are metal oxides, such as iron oxides, which have been proved to have a strong sorption and inactivation effect on viruses (Chu *et al.*, 2001). Moreover, biomineralisation has a short reaction time and high metallogenic efficiency. Thus, it can also be applied to provide adsorption sites for bio-flocculants for the virus in water-contaminated areas.

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

### STABILISATION/SOLIDIFICATION

Stabilisation/solidification (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 SARS-CoV-2, S/S can also be applied to SARS-CoV-2-contaminated soils. Appropriate reagents should be selected to inactivate and stabilise the virus quickly, 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 stabilisation reagents for the inactivation of 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 ozonised water could be used as an alternative. Using the aforementioned reagents to treat pathogenic-virus-contaminated soils is referred to as soil stabilisation. 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, geopolymers and other types of novel binders with high early strength, low permeability and diffusivity and high resistance to climate change can be considered (Du *et al.*, 2020; Haque and Chen, 2019; Jiang *et al.*, 2018; Qiao *et al.*, 2010; Wu *et al.*, 2018; Xia *et al.*, 2019a, 2019b; 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 the authors have a large number of S/S remediation experiences, the synergistic mechanism of the disinfection of SARS-CoV-2 is still unclear. Furthermore, for lab-scale tests for screening appropriate reagents and optimising dosages, as well as for field demonstration tests for validating 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 the discipline.

#### GROUNDWATER REMEDIATION

The improper use of medical waste devices and the leakage of medical waste water can cause waste water containing pathogens to pollute groundwater through soil infiltration (Xu *et al.*, 2020). Casanova and Weaver (2015) suggested that an enveloped virus could survive in sewage for 6–7 days. Hence, it is indispensable to treat groundwater suspected to contain pathogenic microorganisms. If necessary, groundwater contaminated with SARS-CoV-2 in centralised 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 a positive charge should be considered for the removal of the virus (Zhan *et al.*, 2014). Shen *et al.* (2010) utilised bacteriophage phiX174 as the virus indicator, demonstrating that alpha-iron (III) oxide ($\alpha$-$Fe_2O_3$) nanoparticles achieved a nearly 100% adsorption rate for low-concentration viruses ($1 \times 10^3$ plaque-forming units/ml). Mazurkow *et al.* (2020) prepared spray-dried alumina granules, modified with copper (oxide) nanoparticles, to assess the effect of the copper oxidation state on the virus removal capacity. These authors showed that copper (I) oxide ($Cu_2O$) 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 contaminated with pathogens. Materials containing titanium dioxide ($TiO_2$) can decompose oxygen into hydroxyl groups ($\cdot OH$) and superoxide anions ($O^{2-}$) under ultraviolet (UV) irradiation, which might destroy the structure of viruses and play a disinfecting role. Cui *et al.* (2010) showed that the anatase nano-titanium dioxide sol was effective in eliminating the H9N2 AIV under UV irradiation with a wavelength of 365 nm. The ectopic treatment of pathogen-contaminated waste water by photocatalysis can be achieved by groundwater extraction through a light-transmissive reaction column equipped with catalytic materials.

In addition to the aforementioned methods, the use of a reverse-osmosis membrane, with a pore size of 0.5–10 nm, 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 waste-water-treatment processes also needs to be considered.

The aforementioned ideas are only at the incubation stage. The role of environmental geotechnics should be enhanced by efforts in contaminated soil remediation, and research on technologies for remediating SARS-CoV-2-contaminated soils should be actively carried out. More importantly, it is necessary to investigate the problems arising from the remediation of contaminated soils by this virus. Safeguarding 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 materials science researchers to establish well-defined protocols that address both health and legal issues.

### Development of new materials for the remediation of pathogen-contaminated soil

SARS-CoV-2 can enter the soil and groundwater by a range of pathways: the disposal and discharge of solid and fluid medical wastes (MWs); the discharge of patients' and suspects' faeces, which were found to contain SARS-CoV-2 (Xu *et al.*, 2020); and sputum from suspects and infected people who have not been detected. SARS-CoV-2 was reported to live from 4 to 72 h on environmental surfaces, depending on the nature of the surface material (van Doremalen *et al.*, 2020). However, a recent report from the US Centers for Disease Control and Prevention suggested that the virus can survive for 17 days in the environment (Moriarty *et al.*, 2020). Therefore, the transport and spread of the virus through 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. Particularly in 'hotspot' 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 hotspot areas, additives could also be amended to the soil to immobilise 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. Electrokinetic geosynthetics could also be considered for drainage in such cases.

The environmental geotechnics community should develop high-performance sorbents that can adsorb the virus from groundwater (in pump-and-treat and PRB systems) or immobilise 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 iron (II,III) oxide ($Fe_3O_4$)–silicon dioxide ($SiO_2$), which after modification possesses protonic amino groups with a cationic charge so that the prepared magnetic iron (II,III) oxide–silicon dioxide–$NH_2$ nanoparticles can adsorb the negatively charged virus. As a positively charged sorbent, layered double hydroxides have shown excellent performance in removing anionic contaminants (Yu *et al*., 2017), and their use therefore is 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 as a sorbent of viruses and bacteria has been already studied (Cookson, 1969; Meynet *et al*., 2012; Sasidharan *et al*., 2016). The attraction is due to electrostatic forces between the pathogens and carbon. The effects of pH and ionic strength indicated that carboxyl groups, amino groups and the virus's tail fibres are involved in the attachment of the virus to carbon. Such studies can modify ongoing experiments on the adsorption of heavy metals and organic pollutants, but these 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 antibacterial/virus geotextile filters can also be investigated (Silva and Palmeira, 2019).

Materials that help 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 (copper (I) oxide), sulfide (copper (I) sulfide ($Cu_2S$)), iodide (copper (I) iodide (CuI)) and chloride (copper (II) chloride ($CuCl_2$)) were shown to kill viruses effectively within 0.5 or 1 h (Sunada *et al*., 2012). Therefore, the environmental geotechnics community should work together with materials scientists and engineers to develop novel and effective materials for eliminating SARS-CoV-2 from the geoenvironment.

Biogeotechnical engineering has been applied in erosion control and slope stabilisation. Biotechnology has recently been applied in the remediation of petrochemical-contaminated soils by releasing bacteria that consume high volumes of diesel during their lifespan 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 lifespan has been tried through electrokinetic processes for soil pH stabilisation (Hassan *et al*., 2018). 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 neutralise 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 MW. The production of new types of waste that may contain pathogens, such as MSW from households with people in isolation, people who have tested positive for 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 on the sorting and separation of materials from MSW during these times and the recycling of products that might 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 degrade.

MSW contaminated with SARS-CoV-2 can be treated in the same way as regular MW. Presently, two processes are usually adopted for MW destruction (e.g. Italian Parliament, 1997; MEEC, 2020): (*a*) high-temperature steam sterilisation and landfilling after crushing (MEEC, 2006) and (*b*) 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 a significant quantity reduction (Deng *et al*., 2014; Makarichi *et al*., 2018; Windfeld and Brooks, 2015). This method has been widely applied in developed countries and will be the mainstream method for dealing 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 a 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 might 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 the USA? Moreover, what is going to happen if waste contaminated with SARS-CoV-2 is added, originating from households with members who tested positive and are 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 for storing, collecting and disposing of such waste, at the same time taking measures to minimise the risk not only 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 sterilisation and incineration no longer poses health threats, as the infectivity, perniciousness and vulnerability are eliminated, its disposal and recycling during this pandemic is challenging due to the following reasons.

- Need for managing a large volume of MW in the short term. A rapid increase in MW production by as much as six times that of under normal conditions has been observed in China, Poland and the Czech Republic. In Italy, temporary disposal areas have been authorised 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 with an adequate thickness to avoid dispersion in the air).
- Increased ecological concern on the landfill waste mass. During the pandemic, the type and composition of 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 paper delve extensively into this issue.
- Random disposal of MW by the 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 dealt with similarly. Hence, the presence of these materials in MSW could lead to a substantial change in the composition of MSW, particularly 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.
- 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 using gypsum and pulverised 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 clinker with more MW as a binder for soil modification/stabilisation 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 the Netherlands (Mao *et al*., 2020) on the presence of the virus in waste waters, another challenge will be safely managing potentially generated leachate or surface run-off 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 GM 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 Covid-19 where mass casualties 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 the unavailability of facilities and time. Still, often, as was observed on 10 April 2020, in New York City, existing graveyards might have insufficient capacity or some deceased people might not be claimed by relatives, and mass burial is used. The WHO has recommended guidelines for mass burials, but these guidelines have not incorporated the latest technologies that can help minimise health risks to workers that conduct burials and the general public. GCLs 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 and 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 and so on (Scudamore *et al*., 2002). Monitoring systems were implemented at these sites to measure continuously the pollution in the area. Another example is the H1N1 outbreak in the USA 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 has left the world crippled, the significance of geostructures that support essential critical infrastructures providing water, energy, transportation and food has become apparent. The US Cybersecurity and Infrastructure Security Agency in 2020 has identified the essential critical infrastructure as shown in Figure 2, and environmental geotechnics principles lie along the lines to ensure the 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 labour-required maintenance during a lockdown. Consequently, solutions to the present and future challenges will greatly benefit from the advancement in areas such as (*a*) sustainable and resilient infrastructure operations, (*b*) contactless and fast deployment of sensing systems for field monitoring, (*c*) fast deployment of site investigation equipment in extreme environments, (*d*) new-era materials such as geopolymers to replace Portland-cement-based concrete and (*e*) artificial-intelligence-integrated field operations.

Civil infrastructure and its proper functioning are critical to the well-being of people's daily lives, particularly during the Covid-19 pandemic, when people are required to practice social distancing for their protection and for preventing the transmission of the virus. Within this, among other essentials, are core requirements for clean drinking water supply, waste water 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 affected 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, particularly on 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 (MercoPress, 2020). This issue may become of importance to rural regions of poor countries, where clean-water networks might not have been installed, and people might 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 a miracle constructing 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 obtaining soil and environmental quality data quickly included the Geo-Env-Mobility Measuring and Monitoring (GEM3) mobile station, shown in Figure 3, which was developed at Nanyang Technological University (NTU), Singapore. This station is equipped with site investigation equipment such as that for cone penetration testing (CPT) or seismic CPT. It can take soil samples and water samples rapidly and can carry out geophysical tests, such as shear wave and electrical soil resistivity tests. It hosts a three-dimensional 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

Figure 2. Essential infrastructure identified after Covid-19

Figure 3. GEM3 mobile station for rapid geotechnical, environmental and traffic monitoring and testing developed at Nanyang Technological University, Singapore

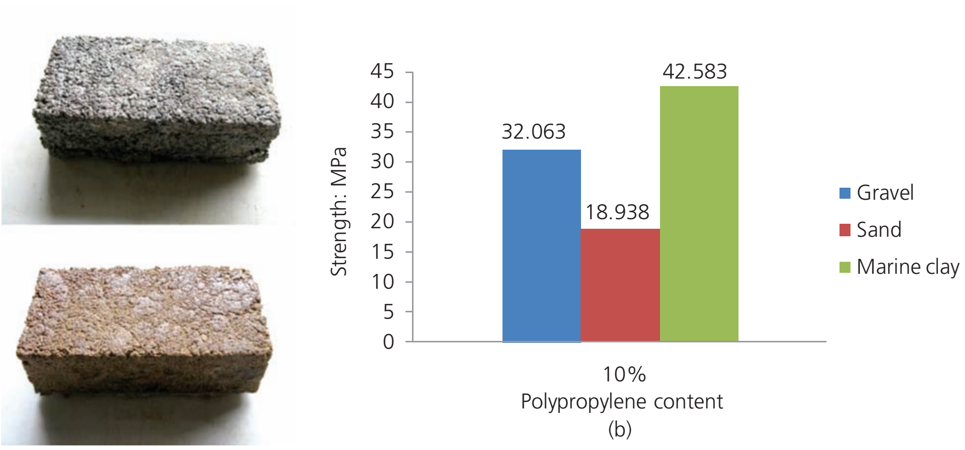
organics in the subsurface environment without the requirement for obtaining soil or water samples.

Novel foundation types and ground-anchoring systems that can be constructed without using specialised equipment need to be developed to meet emergencies, where time is of the essence for the construction of health facilities. Portland cement is normally used for this purpose. However, cement needs to be cured 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 Figure 4(a)) can harden in minutes, and the treated soil has high strength as shown in Figure 4(b). 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 pull-out/uplift forces and compression forces and provide ground improvement – which can be quickly installed and then immediately deployed for anchoring tented structures including field hospitals.

## Potential detoxification of SARS-CoV-2 by zeolite

The human body becomes infected due to toxins present in the external environment, which results in acidosis of the body (Kiki, 2019). In the context of the ongoing pandemic, it has been learned that 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 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 a viral infection event.

The shape and size of the virus are shown on the electron microscopy image in Figure 5, with the shape of the virus being round, elliptic or pleomorphic and its size from around 20–30 nm (Preidt, 2020) to 60–140 nm (Cascella *et al.*, 2020). Such size in the nanoscale range hints that the surface of the coronavirus is probably negatively charged (Verma *et al.*, 2006). Also, the virus has an outer envelope as glycoprotein – that is, 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 μm, mucus and saliva (e.g. sodium ($Na^+$), potassium



(a)

(b)

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

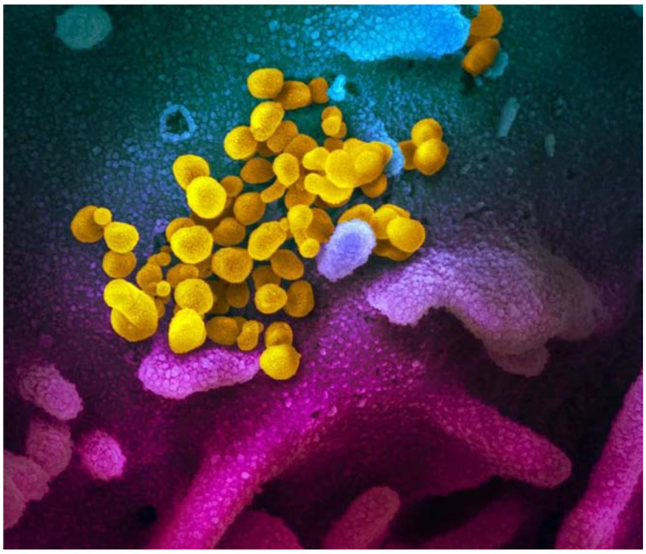


**Figure 5.** Scanning electron microscopy image of SARS-CoV-2 or 2019 novel coronavirus (coloured in yellow), the virus that causes Covid-19, isolated from a patient in the USA, emerging from the surface of cells (blue/pink) cultured in the lab (NIH, 2020)

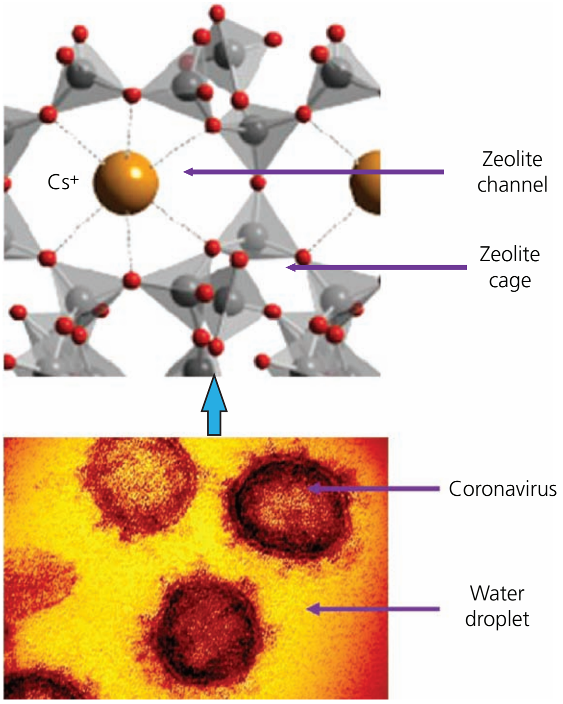


**Figure 6.** Pictorial model of the absorption of the virus in water droplets by zeolite during detoxification. Top image: zeolite (Pavelić *et al.*, 2018). Bottom image: cluster of SARS-CoV-2 (Niaid, 2020)

($K^+$) and chloride ($Cl^-$) ions), 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 become neutralised in the water droplets. In this condition, the concentration of water hydrogen ($H^+$) ions may be higher than that of 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 droplet, the agglomerate (i.e. positive or neutral in nature) may be absorbed by using a molecular sieve powder (i.e. clinoptilolite-type natural pure zeolite (Jha and Singh, 2016; Kiki, 2019) with negatively charged channels and cages) as a detox (i.e. edible/chewable pellet) of zeolite powder (Pavelić *et al.*, 2018). As shown in Figure 6, once absorption of a water droplet (with the virus) occurs with the conceptualised use of zeolite (absorbent, cation exchanger), the absorption could be considered a detoxification process. However, such an application of zeolite as a detox for the targeted virus present in humans needs to be explored meticulously through proper experimentation, for a feasibility study, practically allowed zeolite dose, benefits and side effects and so on. 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 sanitisation on utilisation of biosolids and agricultural activities

The sanitisers or disinfectants used during the Covid-19 pandemic – namely, sodium hypochlorite (NaClO) and calcium hypochlorite ($Ca(ClO)_2$) – consist of oxidising groups (viz. hypochlorite ($ClO^-$), chlorate ($ClO_3^-$) 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 sanitisers 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, due to 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 waste-water-treatment systems. The presence of higher amounts of sodium (Na)- and calcium (Ca)-based compounds and less treated and stabilised 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 sodium and calcium ($Ca^{2+}$) ion complexes in the presence of organic matter, which is available in biosolids, could further hinder the utilisation of biosolids.

On the other hand, agricultural activities could be negatively impacted by the irrigation of crops with water contaminated with sodium and calcium cations existing in the disinfectants, owing to an increase in the sodium adsorption ratio (Rao *et al.*, 2002). Further, the 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 effect of disinfectants on the abundance of NFB and the nitrogen fixation capacity of soils should be investigated. In this regard, the effect of landfill-mined-soil-like fractions (LFMSFs), obtained from landfill-mining activity, should be investigated in order to enhance the growth of NFB in soils contaminated with disinfectants and to promote the utilisation of LFMSFs 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 introduced chaos theory, which was used initially to study the dynamics of turbulent flow and which considers 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 possible only for specific time windows (which 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, 1996). The SARS-CoV-2 pandemic could be seen as a complex system, such as coronaviruses (normally under control through vaccines) when entering the chaotic state. This means, in other words, that the capability to make short- and long-term effective predictions is lost, as illustrated in Figure 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: p. 8).

Environmental geotechnics, for example, when dealing with the management of polluted sites, is used to facing emblematic cases of different types of complex systems. However, it has been recognised 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 recognised by the US National Research Council (NRC, 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 NRC 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 of 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 in weather and field management for better crop production (Kimura *et al.*, 2008). Microorganisms in soils and sediments adapt to such

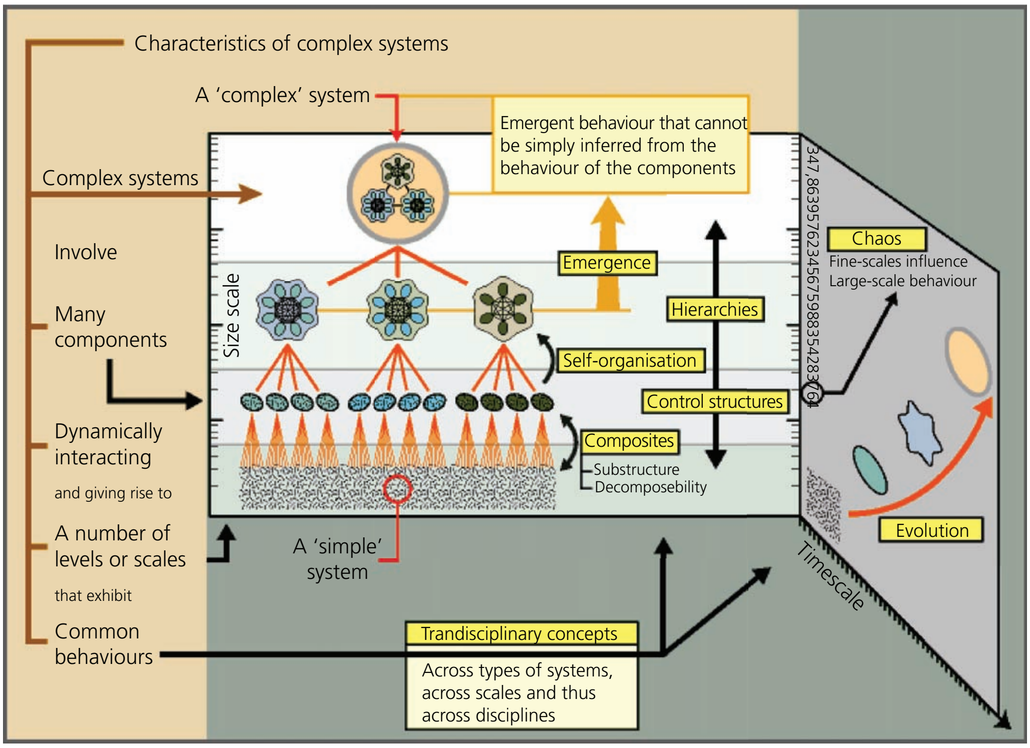


Figure 7. Characteristics of complex systems, from complexity to chaos (Ferreira, 2001)

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 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 UN in their 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 …' (UNDRR, 2019). It is apparent then that the obligation of the environmental geotechnics community in dealing with thermo-chemo-hydro-geomechanical coupling, within multiscale natural systems, is on discerning their true nature and behaviour. It follows that environmental geotechnics professionals can be truly functional if they 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 Swiss Federal Institute of Technology in Zurich, in the past 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 in 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 characterisation and treatment of marine sediments representing part of these activities (Vitone *et al.*, 2016, 2018).

If the characterisation of sediments, in their current contaminated state, has demonstrated that they can represent a complex system, exhibiting a long-term predictable behaviour, the data have also shown that chemo-hydro-mechanical processes can prompt a 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 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 it does not affect the mechanical performance of the binder (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 UN hope when dealing with risk management (UNDRR, 2019). The whole system is considered as a complex system, which exhibits emergent properties that arise from interactions among its constituent parts, more than a complicated system that can be (dis-)assembled and understood as the sum of its parts (Figure 8). Facing complexity means that some uncertainties in any complex system will always remain unmeasurable. However, the risks can be characterised and quantified, to some degree, by networks made up of individual agents whose interactions exert macroscopic consequences feeding back to individual behaviours. Understanding sensitivities to change and system reverberations is 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 have 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 the environmental geotechnics 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 characterisation to remediation, it becomes crucial to develop a holistic understanding of the components and processes of a system, including precursor signals and anomalies, system reverberations and sensitivities to further modifications.

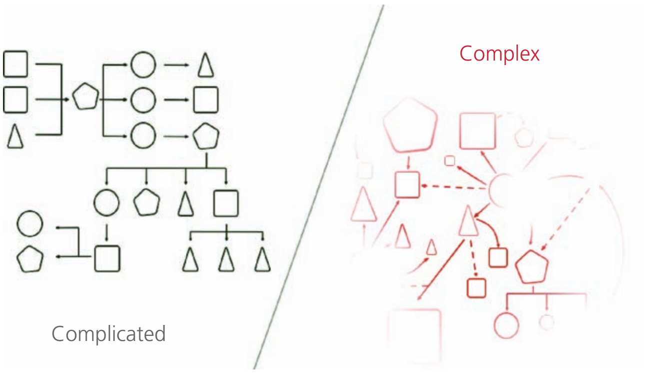


**Figure 8.** Complicated and complex systems (adopted from UNDRR (2019))

The knowledge acquired in the past years related to the Taranto site has brought about the building of a conceptual design site model that includes various multidisciplinary data (chemical, geochemical, hydromechanical and environmental technology) and that can be used to integrate modelling for reliable predictions of the system future development (Sollecito *et al*., 2019; Vitone *et al*., 2018).

### Bayesian framework for quantifying uncertainty in geoenvironmental and epidemiological problems

The development of the Bayesian theory as the mathematical expression of the rules of logic (Cox, 1962; Jeffreys, 1948) 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 a 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 framework much broader than 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 paper.

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 of assessing a hypothesis $H$, after initial information $I$ is supplemented by measured data $D$:

$$P(H|DI) = P(H|I)\frac{P(D|HI)}{P(D|I)} \tag{1}$$

Here, $P(H|I)$ is denoted as the prior probability of $H$ given $I$ (but prior to obtaining $D$) and $P(H|DI)$ is the posterior probability of $H$ after both $D$ and $I$. The preceding expression provides the mechanism not only for updating the uncertainty assessment as new information becomes available but also for utilising 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, the Bayesian theory through tools, such as Equation 1, provides the mathematics for evaluating the cohesion and consistency of logical structures – that is, of conceptual models, such as of those discussed in the section 'Environmental geotechnics and the challenge of complexity' 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 updating of probabilities, thus reflecting at each point the state of knowledge.

As such, the Bayesian theory has a long history of application in public health and medical studies, such as for the analysis of clinical trials (e.g. Biswas *et al*., 2009; Etzioni and Kadane, 1995; Schoenfeld *et al*., 2009; Spiegelhalter *et al*., 2004;), for studies in population genetics (e.g. Beerli, 2006; Sorensen and Gianola, 2002), for estimation of the neurodevelopmental health effects of multi-pollutant metal mixtures and the toxicological impacts of air pollutants (Bobb *et al*., 2015), for evaluation of diagnostic protocols (Broemeling, 2007), for elucidation of 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 the following: (*a*) the use of prior information reduces the need for large sample sizes and provides more precision and flexibility in decision making; (*b*) the iterative updating capability of the Bayesian method allows for mid-course correction during a trial design or changes in the sequence and size of trials; and (*c*) 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 …' (CBER, 2010: p. 8).

Bayesian hierarchical models were reported on 30 March 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, have found many applications in several geoenvironmental problems, which span earthquake and soil degradation (e.g. Ching and Glaser, 2003; Corral, 2005), soil and rock excavation studies (e.g. D'Or *et al*., 2001; Gens *et al*., 1988), risks from flooding (e.g. Solana-Ortega and Solana, 2001; van Gelder, 1996), incineration air pollution problems (e.g. Paleologos *et al*., 2018), groundwater contamination problems (e.g. Woodbury and Rubin, 2000; Ye *et al*., 2004) and environmental risk studies (Lerche and Paleologos, 2001; Mohamed and Paleologos, 2017), among others. Bayesian methods have a long record in the development of stochastic governing equations describing flow and contaminant transport in the unsaturated zone (e.g. 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), and of karst spring discharge (Hao *et al*., 2015), to infer nitrogen loadings from crop types (Ransom *et al*., 2018). The

Bayesian framework is so versatile that the same researcher can apply it to both geoenvironmental and public health problems (see e.g. Christakos and Serre, 2000; Christakos *et al.*, 2007). Given the significance of the Bayesian approach as a tool in 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 Covid-19

The challenges that the Covid-19 pandemic 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 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, which requires the help of experts in the field of pathogens. Not only that, but guidance is also needed from experts in the infectious disease field and related medical fields to establish professional laboratories that meet safety standards, to carry out collaborative tests and to 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, co-operation with experts in the field of materials 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 renormalisation 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 multidisciplinary 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 that with the existing pandemic, some rethinking 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 and the European Space Agency (ESA) have recently published satellite images that captured a significant reduction in air pollution and carbon dioxide ($CO_2$) 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 with a lasting effect. However, these changes prove that many environmental problems require international co-operation urgently, as Saadi of Shiraz (1184–1283) stated 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 realisation of importance of international co-operation 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). Figure 9 (Morens and Fauci, 2007) shows that the first wave started approximately in the late spring of 1918, peaking in October–November of that year and subsiding and

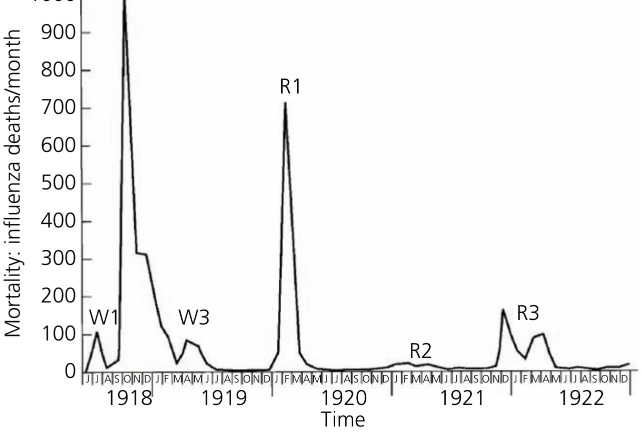


Figure 9. Monthly influenza-associated mortality in Breslau, Silesia (now Wroclaw, Poland), from June 1918 through December 1922 (Morens and Fauci, 2007). R, recurrence; W, wave

almost disappearing during 1919. It reappeared 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 reappearance in November of 1921 that lasted until April of 1922. About 500 million people was 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 World War II, where the number of deaths is estimated to have exceeded 75 million people and is more than double the number of deaths caused by World War I. At present, no one knows if there will be a second or a third wave of the Covid-19 pandemic like that of 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 having 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 paper 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 help the society better. Some important research topics and directions are proposed.

- Environmental geotechnics has long been dedicated to using multidisciplinary perspectives, techniques and methods to solve environmentally related geotechnical engineering problems. In response to the geoenvironmental effects caused by Covid-19, the environmental geotechnics 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.
- It is imperative for the environmental geotechnics community to perform a systematic study to reveal the mechanisms of pathogen–soil interactions and the impact on soil engineering properties. This is a fundamental step in formulating accurate environmental and geotechnical interactions.
- Understanding pathogen transport mechanisms and their controlling factors in the subsurface is essential for taking countermeasures for containing and remediating pathogen-contaminated sites. According to the characteristics of SARS-CoV-2-contaminated soils or groundwater, it is necessary to develop new technologies in co-operation 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.
- Environmental geotechnics researchers should work together with materials scientists and engineers to develop novel and high-performance materials that will prevent SARS-CoV-2 from entering the geoenvironment.
- In principle, municipal waste contaminated with SARS-CoV-2 can be treated similarly as MW by sterilisation 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.
- 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.
- Development of models for simulating SARS-CoV-2 transmission in the geoenvironment with emphasis on multiscale and non-linear dynamic descriptions of complex systems would significantly improve predictive capabilities.
- 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 multidisciplinary efforts linking environmental geotechnics, public health and medical researchers.
- Strengthening pandemic-induced environmental risk assessment and management would benefit both in reducing risks and in developing mitigation design strategies.
- Because the challenges brought by the Covid-19 pandemic are multifaceted, it is recommended that multidisciplinary research be 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 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 the community to be more united, inclusive and far-sighted than ever.

## Acknowledgements

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

## REFERENCES

Abarbanel H (1996) *Analysis of Observed Chaotic Data*. Springer, New York, NY, USA.

Atkinson J, Chartier Y, Pessoa-Silva CL *et al.* (eds) (2009) Annex C: Respiratory droplets. In *Natural Ventilation for Infection Control in Health-care Settings*. World Health Organization, Geneva, Switzerland, pp. 77–81. See https://www.ncbi.nlm.nih.gov/books/NBK143281/ (accessed 30/04/2020).

Baranger M (2002) *Chaos, Complexity, and Entropy: a Physics Talk for Non-physicists*. New England Complex Systems Institute, Cambridge, MA, USA. See http://necsi.org/projects/baranger/cce.pdf (accessed 30/04/2020).

Bareither CA, Wolfe GL, McMahon KD and Benson CH (2013) Microbial diversity and dynamics during methane production from municipal solid waste. *Waste Management* **33(10)**: 1982–1992, https://doi.org/10.1016/j.wasman.2012.12.013.

Barlaz MA, Schaefer DM and 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, https://doi.org/10.1128/aem.55.1.55-65.1989.

Beerli P (2006) Comparison of Bayesian and maximum-likelihood inference of population genetic parameters. *Bioinformatics* **22(3)**: 341–345, https://doi.org/10.1093/bioinformatics/bti803.

Bitton G and Harvey RM (1992) Transport of pathogens through soils and aquifers. In *Environmental Microbiology* (Mitchell R (ed.) Wiley-Liss, New York, NY, USA, pp. 103–124.

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

Bo MW (2011) Historical advancements of geotechnical engineering and their application in the construction industry and beyond. In *Proceedings of the First International Conference in Advancement in Geotechnical Engineering, Perth, Australia*, pp. 45–58.

Bo MW (2014) Role of environmental geotechnics. *Environmental Geotechnics* **1(4)**: 198, https://doi.org/10.1680/envgeo.13.00081.

Bobb JF, Valeri L, Claus Henn B *et al.* (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 *et al.* (2020) Effects of hand disinfection with alcohol hand rub, ozonized water or soap water – time for reconsideration? *Journal of Hospital Infection*, https://doi.org/10.1016/j.jhin.2020.03.014.

Broemeling LD (2007) *Bayesian Biostatistics and Diagnostic Medicine*. Chapman and Hall/CRC, Boca Raton, FL, USA.

Carducci A, Federigi I and Verani M (2013) Virus occupational exposure in solid waste processing facilities. *Annals of Occupational Hygiene* **57(9)**: 1115–1127, https://doi.org/10.1093/annhyg/met043.

Casanova LM and Weaver SR (2015) Inactivation of an enveloped surrogate virus in human sewage. *Environmental Science & Technology Letters* **2(3)**: 76–78, https://doi.org/10.1021/acs.estlett.5b00029.

Cascella M, Rajnik M, Cuomo A, Dulebohn SC and Di Napoli R (2020) *Features, Evaluation and Treatment Coronavirus (COVID-19)*. StatPearls Publishing, Treasure Island, FL, USA. See https://www.ncbi.nlm.nih.gov/books/NBK554776/ (accessed 30/04/2020).

CBER (Center of Biologics Evaluation and Research) (2010) *Guidance for the Use of Bayesian Statistics in Medical Device Clinical Trials*. CBER, Rockville, MD, USA. See www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-use-bayesian-statistics-medical-device-clinical-trials.

CDC (US Centers for Disease Control and Prevention) (2019) *1918 Pandemic (H1N1 Virus)*. US CDC, Atlanta, GA, USA. See https://www.cdc.gov/flu/pandemic-resources/1918-pandemic-h1n1.html (accessed 30/04/2020).

Chandana N, Goli VSNS, Mohammad A and Singh DN (2020) Characterization and utilization of landfill-mined-soil-like-fractions (*LFMSF*) for sustainable development: a critical appraisal. *Waste and Biomass Valorization*, https://doi.org/10.1007/s12649-020-01052-y.

Chen QL, Li H, Zhou XY *et al.* (2017) An underappreciated hotspot of antibiotic resistance: the groundwater near the municipal solid waste landfill. *Science of the Total Environment* **609**: 966–973, https://doi.org/10.1016/j.scitotenv.2017.07.164.

Chen X, Wang M, Hicks MA and 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, https://doi.org/10.1002/nag.2783.

Chen X, Thornton SF and Pao W (2018b) Mathematical model of coupled dual chemical osmosis based on mixture-coupling theory. *International Journal of Engineering Science* **129**: 145–155, https://doi.org/10.1016/j.ijengsci.2018.04.010.

Cheng L, Yang Y and Chu J (2019) In-situ microbially induced $Ca^{2+}$-alginate polymeric sealant for seepage control in porous materials. *Microbial Biotechnology* **12(2)**: 324–333, https://doi.org/10.1111/1751-7915.13315.

Ching J and Glaser SD (2003) Identification of soil degradation during earthquake excitations by Bayesian inference. *Earthquake Engineering and Structural Dynamics* **32**: 845–869, https://doi.org/10.1002/eqe.251.

Christakos G and Serre ML (2000) BME analysis of spatiotemporal particulate matter distributions in North Carolina. *Atmospheric Environment* **34(20)**: 3393–3406, https://doi.org/10.1016/s1352-2310(00)00080-7.

Christakos G, Olea RA and Yu HL (2007) Recent results on the spatiotemporal modeling and comparative analysis of Black Death and bubonic plague epidemics. *Public Health* **121(9)**: 700–720, https://doi.org/10.1016/j.puhe.2006.12.011.

Chu Y, Jin Y, Flury M and Yates MV (2001) Mechanisms of virus removal during transport in unsaturated porous media. *Water Resources Research* **37(2)**: 253–263, https://doi.org/10.1029/2000wr900308.

Chu J, Stabnikov V and Ivanov V (2012) Microbially induced calcium carbonate precipitation on surface or in the bulk of soil. *Geomicrobiology Journal* **29(6)**: 544–549, https://doi.org/10.1080/01490451.2011.592929.

Cookson JT Jr (1969) Mechanism of virus adsorption on activated carbon. *Journal AWWA* **61(1)**: 52–56, https://doi.org/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, https://doi.org/10.5194/npg-12-89-2005.

Cox RT (1962) *The Algebra of Probable Inference*. John Hopkins University Press, Baltimore, MD, USA (reprint of the original 1925 edition).

Cui H, Jiang J, Gu W *et al.* (2010) Photocatalytic inactivation efficiency of anatase nano-$TiO_2$ sol on the H9N2 avian influenza virus. *Photochemistry and Photobiology* **86(5)**: 1135–1139, https://doi.org/10.1111/j.1751-1097.2010.00763.x.

D’Or D, Bogaert P and 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, https://doi.org/10.1007/s004770000057.

Dare R (2000) Book review: Complexity: the Emerging Science at the Edge of Order and Chaos – M. Mitchell Waldrop (1992). *Proceedings of the Research Seminar in Engineering Systems (ESD.83), Cambridge, MA, USA.*

Decrey L and 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, https://doi.org/10.1039/c6ew00311g.

Decrey L, Kazama S, Udert KM and 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, https://doi.org/10.1021/es5044529.

Dejong JT, Soga K, Kavazanjian E *et al.* (2013) Biogeochemical processes and geotechnical applications: progress, opportunities and challenges. *Géotechnique* **63(4)**: 287–301, https://doi.org/10.1680/geot.SIP13.P.017.

Deng N, Cui W, Wang W *et al.* (2014) Experimental study on co-pyrolysis characteristics of typical medical waste compositions. *Journal of Central South University* **21**: 4613–4622, https://doi.org/10.1007/s11771-014-2468-4.

Du YJ, Wu J, Bo YL and 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, https://doi.org/10.1007/s11440-019-00793-y.

Etzioni RD and Kadane JB (1995) Bayesian statistical methods in public health and medicine. *Annual Review of Public Health* **16**: 23–41, https://doi.org/10.1146/annurev.pu.16.050195.000323.

Fang S, Jiang L, Li P, Bai J and Chang C (2020) Study on pyrolysis products characteristics of medical waste and fractional condensation of the pyrolysis oil. *Energy* **195**: article 116969, https://doi.org/10.1016/j.energy.2020.116969.

Federico A, Vitone C and Murianni A (2015) On the mechanical behaviour of dredged submarine clayey sediments stabilized with lime or cement. *Canadian Geotechnical Journal* **52(12)**: 2030–2040, https://doi.org/10.1139/cgj-2015-0086.

Fei X, Zekkos D and 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, https://doi.org/10.1016/j.wasman.2014.10.027.

Ferreira P (2001) Tracing complexity theory. *Proceedings of the Research Seminar in Engineering Systems (ESD.83), Cambridge, MA, USA*. See http://web.mit.edu/esd.83/www/notebook/NewNotebook.htm (accessed 30/04/2020).

Flaxman S, Mishra S, Gandy A *et al.* (2020) *Estimating the Number of Infections and the Impact of Non-pharmaceutical Interventions on COVID-19 in 11 European Countries*. Imperial College COVID-19 Response Team, London, UK. See 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 (accessed 30/04/2020).

Fukuzaki S (2006) Mechanisms of actions of sodium hypochlorite in cleaning and disinfection processes. *Biocontrol Science* **11(4)**: 147–157, https://doi.org/10.4265/bio.11.147.

Gallagher EM (1998) Biological clogging of geocomposites exposed to raw landfill leachate over an extended period. *Waste Management & Research* **16(5)**: 421–429, https://doi.org/10.1177/0734242x9801600504.

Gawande NA, Reinhart DR and Yeh GT (2010) Modeling microbiological and chemical processes in municipal solid waste bioreactor, part I: Development of a three-phase numerical model BIOKEMOD-3P. *Waste management* **30(2)**: 202–210.

Gens A, Ledesma A and Alonso EE (1988) Back analysis using prior information – application to the staged excavation in rock. *Proceedings of the 6th International Conference on Numerical Methods in Geomechanics, Innsbruck, Austria*, pp. 2009–2016.

Gerba CP, Tamimi AH, Pettigrew C, Weisbrod AV and 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, https://doi.org/10.1177/0734242x10397968.

Graiver DA, Topliff CL, Kelling CL and Bartelt-Hunt SL (2009) Survival of the avian influenza virus (H6N2) after land disposal. *Environmental Science & Technology* **43(11)**: 4063–4067, https://doi.org/10.1021/es900370x.

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

Haque MA and Chen B (2019) Research progresses on magnesium phosphate cement: a review. *Construction and Building Materials* **211**: 885–898, https://doi.org/10.1016/j.conbuildmat.2019.03.304.

Hassan I, Mohamedelhassan E, Yanful E and Bo MW (2018) Enhanced electrokinetic bioremediation by pH stabilisation. *Environmental Geotechnics* **5(4)**: 222–233, https://doi.org/10.1680/jenge.16.00001.

He J, Gao Y, Gu Z, Chu J and Wang L (2020) Characterization of crude bacterial urease for $CaCO_3$ precipitation and cementation of silty sand. *Journal of Materials in Civil Engineering* **32(5)**: 04020071, https://doi.org/10.1061/(asce)mt.1943-5533.0003100.

Heo Y, Park J, Lim SI *et al.* (2010) Size-resolved culturable airborne bacteria sampled in rice field, sanitary landfill, and waste incineration sites. *Journal of Environmental Monitoring* **12(8)**: 1619–1624, https://doi.org/10.1039/c0em00004c.

HSPH (Harvard T.H. Chan School of Public Health) (2020) *Air Pollution Linked with Higher COVID-19 Death Rates*. HSHP, Boston, MA, USA. See https://www.hsph.harvard.edu/news/hsph-in-the-news/air-pollution-linked-with-higher-covid-19-death-rates/ (accessed 30/04/2020).

iefimerida (2020) New experimental medicine offers hope. *iefimerida*, 3 April (in Greek) See https://www.iefimerida.gr/ (accessed 03/04/2020).

Italian Parliament (1997) *Italian Legislative Decree no. 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. Italian Parliament, Rome, Italy.

Jacobson KH, Lee S, McKenzie D, Benson CH and Pedersen JA (2009) Transport of the pathogenic prion protein through landfill materials. *Environmental Science & Technology* **43(6)**: 2022–2028, https://doi.org/10.1021/es802632d.

Jaynes ET (2003) *Probability Theory: the Logic of Science*. Cambridge University Press, Cambridge, UK.

Jeffreys H (1948) *Theory of Probability*, 2nd edn. Clarendon Press Oxford, UK (originally published in 1939, later editions 1948, 1961, 1967, 1988).

Jha B and Singh DN (2016) Applications of fly ash zeolites: case studies. In *Fly Ash Zeolites: Innovations, Applications and Directions*. Springer, Singapore, pp. 191–202. See https://www.springer.com/gp/book/9789811014024 (accessed 30/04/2020).

Jiang NJ, Du YJ and 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, https://doi.org/10.1016/j.clay.2018.04.014.

Jiang NJ, Tang CS, Yin LY, Xie YH and Shi B (2019) Applicability of microbial calcification method for sandy slope surface erosion control. *Journal of Materials in Civil Engineering* **31(11)**: article 04019250, https://doi.org/10.1061/(asce)mt.1943-5533.0002897.

Jiang NJ, Tang CS, Hata T *et al.* (2020) Bio-mediated soil improvement: the way forward. *Soil Use and Management* **36(2)**: 185–188, https://doi.org/10.1111/sum.12571.

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 and Burkowska A (2013) Municipal landfill sites as sources of microorganisms potentially pathogenic to humans. *Environmental Science: Processes & Impacts* **15(5)**: 1078–1086, https://doi.org/10.1039/c3em30728j.

Katan J (2017) Diseases caused by soilborne pathogens: biology, management and challenges. *Journal of Plant Pathology* **99(2)**: 305–315, https://doi.org/10.4454/jpp.v99i2.3862.

Khatami HR and 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.

Kiki (2019) *An Introduction to Zeolite*. Kiki Ltd, Aylsham, UK. See https://kiki-health.com/an-introduction-to-zeolite/ (accessed 29/04/2020).

Kimura M, Jia ZJ, Nakayama N and Asakawa S (2008) Ecology of viruses in soils: past, present and future perspectives. *Soil Science & Plant Nutrition* **54**: 1–32, https://doi.org/10.1111/j.1747-0765.2007.00197.x.

Kording KP and Wolpert DM (2004) Bayesian integration in sensorimotor learning. *Nature* **427**: 244–247, https://doi.org/10.1038/nature02169.

Lerche I and Paleologos EK (2001) *Environmental Risk Analysis*. McGraw-Hill, New York, NY, USA.

Li K, Zhang Y, Yeh TCJ *et al.* (2019) An iterative scheme to map and incorporate geologic information of discontinuous heterogeneity in hydraulic tomography. *Journal of Hydrology* **579**: article 124143, https://doi.org/10.1016/j.jhydrol.2019.124143.

Lorenz EN (1963) Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences* **20**: 130–141, https://doi.org/10.1175/1520-0469(1963)020<0130:dnf>2.0.co;2.

Makarichi L, Jutidamrongphan W and Techato K (2018) The evolution of waste-to-energy incineration: a review. *Renewable and Sustainable Energy Reviews* **91**: 812–821, https://doi.org/10.1016/j.rser.2018.04.088.

Malham SK, Rajko-Nenow P, Howlett E *et al.* (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, https://doi.org/10.1039/c4em00031e.

Mao K, Zhang H and Yang Z (2020) Can a paper-based device trace COVID-19 sources with wastewater-based epidemiology? *Environmental Science & Technology* **54(7)**: 3733–3735, https://doi.org/10.1021/acs.est.0c01174.

Matsumoto T, Sunada K, Nagai T *et al.* (2019) Preparation of hydrophobic $La_2Mo_2O_9$ ceramics with antibacterial and antiviral properties. *Journal of Hazardous Materials* **378**: article 120610, https://doi.org/10.1016/j.jhazmat.2019.05.003.

Mazurkow JM, Yüzbasi NS, Domagala KW *et al.* (2020) Nano-sized copper (oxide) on alumina granules for water filtration: effect of copper oxidation state on virus removal performance. *Environmental Science & Technology* **54**: 1214–1222, https://doi.org/10.1021/acs.est.9b05211.

McDougall J (2007) A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste. *Computers and Geotechnics* **34(4)**: 229–246, https://doi.org/10.1016/j.compgeo.2007.02.004.

Mechref Y and Novotny MV (2007) Capillary electrophoresis | glycoproteins. In *Encyclopedia of Separation Science* (Wilson ID (ed.)). Academic Press, San Diego, CA, USA, pp. 1–15. See https://www.sciencedirect.com/topics/chemistry/glycoprotein (accessed 30/04/2020).

MEEC (Ministry of Ecology and Environment of the People's Republic of China) (2003) *Technical Codes of Medical Wastes Centralized Disposal*. MEEC, Beijing, China.

MEEC (2006) *Technical Specifications for Steam-based Centralized Treatment Engineering on Medical Waste*. MEEC, Beijing, China.

MEEC (2020) *Disposal Management and Technical Guide of Emergent COVID-19 Medical Waste*. MEEC, Beijing, China.

MercoPress (2020) 'Contaminated drinking water' in Rio: run on bottled-water in supermarkets. *MercoPress*, 16 January. See https://en.mercopress.com/2020/01/16/contaminated-drinking-water-in-rio-run-on-bottled-water-in-supermarkets (accessed 29/04/2020).

Meynet P, Hale SE, Davenport RJ *et al.* (2012) Effect of activated carbon amendment on bacterial community structure and functions in a PAH impacted urban soil. *Environmental Science & Technology* **46(9)**: 5057–5066, https://doi.org/10.1021/es2043905.

Mitchell JK and Santamarina JC (2005) Biological considerations in geotechnical engineering. *Journal of Geotechnical and Geoenvironmental Engineering* **131(10)**: 1222–1233, https://doi.org/10.1061/(asce)1090-0241(2005)131:10(1222).

Mohamed AMO and Paleologos EK (2017) *Fundamentals of Geoenvironmental Engineering*. Butterworth-Heinemann, Oxford, UK.

Morales I, Atoyan JA, Amador JA and Boving T (2014) Transport of pathogen surrogates in soil treatment units: numerical modeling. *Water* **6**: 818–838.

Morens DM and Fauci AS (2007) The 1918 influenza pandemic: insights for the 21st century. *Journal of Infectious Diseases* **195(7)**: 1018–1028, https://doi.org/10.1086/511989.

Moriarty LF, Plucinski MM, Marston BJ *et al.* (2020) Public health responses to COVID-19 outbreaks on cruise ships – worldwide, February–March 2020. *Morbidity and Mortality Weekly Report* **69(12)**: 347–352, https://doi.org/10.15585/mmwr.mm6912e3.

Niaid (US National Institute of Allergy and Infectious Diseases) (2020) *New Images of Novel Coronavirus SARS-CoV-2 Now Available*. Niaid, Rockville, MD, USA. See https://www.niaid.nih.gov/news-events/novel-coronavirus-sarscov2-images (accessed 29/04/2020).

NIH (US National Institutes of Health) (2020) *New Coronavirus Stable for Hours on Surfaces: SARS-CoV-2 Stability Similar to Original SARS Virus*. NIH, Bethesda, MD, USA. See https://www.nih.gov/news-events/news-releases/new-coronavirus-stable-hours-surfaces (accessed 29/04/2020).

NRC (US National Research Council) (1994) *Alternatives for Groundwater Cleanup*. The National Academies Press, Washington, DC, USA.

O'Kelly BC, Brinkgreve RBJ and 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 and El Amrousi M (2018) Bayesian analysis of air emission violations from waste incineration and co-incineration plants. *Risk Analysis* **38(11)**: 2368–2378, https://doi.org/10.1111/risa.13130.

Palmeira EM, Remigio AFN, Ramos MLG and Bernardes RS (2008) A study on biological clogging of nonwoven geotextiles under leachate flow. *Geotextiles and Geomembranes* **26(3)**: 205–219, https://doi.org/10.1016/j.geotexmem.2007.10.006.

Pavelić SK, Medica JS, Gumbarević D *et al.* (2018) Critical review on zeolite clinoptilolite safety and medical applications *in vivo*. *Frontiers in Pharmacology* **9**: article 1350, https://doi.org/10.3389/fphar.2018.01350.

Potts D, Gorres J, Nicosia E and Amador J (2004) Effects of aeration on water quality from septic system leachfields. *Journal of Environmental Quality* **33**: 1828–1838.

Preidt R (2020) Coronavirus isn't even 'alive', but experts explain how it can harm. *MedicineNet*, 26 March. See https://www.medicinenet.com/script/main/art.asp?articlekey=229387 (accessed 30/04/2020).

Qiao F, Chau CK and Li Z (2010) Property evaluation of magnesium phosphate cement mortar as patch repair material. *Construction and Building Materials* **24(5)**: 695–700, https://doi.org/10.1016/j.conbuildmat.2009.10.039.

Quanrud DM, Carroll SM, Gerba CP and Arnold RG (2003) Virus removal during simulated soil-aquifer treatment. *Water Research* **37(4)**: 753–762, https://doi.org/10.1016/s0043-1354(02)00393-7.

Ransom KM, Bell AM, Barber QE, Kourakos G and 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. *Hydrology and Earth System Sciences* **22(5)**: 2739–2758, https://doi.org/10.5194/hess-22-2739-2018.

Rao DLN, Giller KE, Yeo AR and Flowers TJ (2002) The effects of salinity and sodicity upon nodulation and nitrogen fixation in chickpea (*Cicer arietinum*). *Annals of Botany* **89**: 563–570, https://doi.org/10.1093/aob/mcf097.

Reinhart DR and Townsend TG (1998) *Landfill Bioreactor Design and Operation*. Lewis Publishers, Boca Raton, FL, USA.

Rowe RK, Quiley RM, Brachman RWI and Booker JR (2004) *Barrier System for Waste Disposal Facilities*. CRC Press, London, UK.

Rzezutka A and Cook N (2004) Survival of human enteric viruses in the environment and food. *FEMS Microbiology Reviews* **28(4)**: 441–453, https://doi.org/10.1016/j.femsre.2004.02.001.

Sasidharan S, Torkzaban S, Bradford SA *et al.* (2016) Transport and retention of bacteria and viruses in biochar-amended sand. *Science of the Total Environment* **548**: 100–109, https://doi.org/10.1016/j.scitotenv.2015.12.126.

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

Scudamore JM, Trevelyan GM, Tas MV, Varley EM and 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, https://doi.org/10.20506/rst.21.3.1377.

Sharma S and Singh DN (2015) Characterization of sediments for sustainable development: state of the art. *Marine Georesources and Geotechnology* **33(5)**: 447–465, https://doi.org/10.1080/1064119x.2014.953232.

Shen L, Zhao B, Zhang J, Chen J and 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, https://doi.org/10.1631/jzus.A1000244.

Silva S and Palmeira EM (2019) Leachate pre-treatment using non-woven geotextile filters. *Environmental Geotechnics* **6(1)**: 34–46, https://doi.org/10.1680/jenge.16.00021.

Sivakumar V, O'Kelly BC, Madhav MR, Moorhead C and 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 and Solana V (2001) Entropy-based inference of simple physical models for regional flood analysis. *Stochastic Environmental Research and Risk Assessment (SERRA)* **15**: 415–446, https://doi.org/10.1007/s004770100079.

Sollecito F, Vitone C, Miccoli D *et al.* (2019) Marine sediments from a contaminated site: geotechnical properties and chemo-mechanical coupling processes. *Geosciences* **9(8)**: article 333, https://doi.org/10.3390/geosciences9080333.

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* **3(2)**: 79–82, https://doi.org/10.4103/JNSM.JNSM_22_20.

Song L, Li L, Yang S *et al.* (2016) Sulfamethoxazole, tetracycline and oxytetracycline and related antibiotic resistance genes in a large-scale landfill, China. *Science of the Total Environment* **551**: 9–15, https://doi.org/10.1016/j.scitotenv.2016.02.007.

Sorensen D and Gianola D (2002) *Likelihood, Bayesian and MCMC Methods in Quantitative Genetics*. Springer, New York, NY, USA.

Spiegelhalter DJ, Abrams KR and Myles JP (2004) *Bayesian Approaches to Clinical Trials and Health-care Evaluation*. Wiley, Chichester, UK.

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

Staley BF, Francis L and 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, https://doi.org/10.1128/AEM.02349-10.

Sunada K, Minoshima M and Hashimoto K (2012) Highly efficient antiviral and antibacterial activities of solid-state cuprous compounds. *Journal of Hazardous Materials* **235**: 265–270, https://doi.org/10.1016/j.jhazmat.2012.07.052.

Tang CS, Yin LY, Jiang NJ *et al.* (2020) Factors affecting the performance of microbial-induced carbonate precipitation (MICP) treated soil: a review. *Environmental Earth Sciences* **79**: article 94, https://doi.org/10.1007/s12665-020-8840-9.

Todaro F, Vitone C and Notarnicola M (2019) Stabilization and recycling of contaminated marine sediments. *E3S Web of Conferences* **92**: article 11004, https://doi.org/10.1051/e3sconf/20199211004.

UNDRR (UN Office for Disaster Risk Reduction) (2019) *Global Assessment Report on Disaster Risk Reduction: 2019*. UNDRR, Geneva, Switzerland. See https://gar.undrr.org/sites/default/files/reports/2019-05/full_gar_report.pdf (accessed 30/04/2020).

van Doremalen N, Bushmaker T, Morris DH *et al.* (2020) Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *New England Journal of Medicine* **382**: 1564–1567, https://doi.org/10.1056/NEJMc2004973.

van Gelder PHAJM (1996) A Bayesian analysis of extreme water levels along the Dutch coast using flood historical data. *Stochastic Hydraulics* **7**: 243–251.

Vaverkova MD, Adamcova D, Winkler J *et al.* (2019) Influence of a municipal solid waste landfill on the surrounding environment: landfill vegetation as a potential risk of allergenic pollen. *International Journal of Environmental Research and Public Health* **16(24)**: article 5064, https://doi.org/10.3390/ijerph16245064.

Verma S, Bednar V, Blount A and Hogue BG (2006) Identification of functionally important negatively charged residues in the carboxy end of mouse hepatitis coronavirus A59 nucleocapsid protein. *Journal of Virology* **80(9)**: 4344–4355, https://doi.org/10.1128/JVI.80.9.4344-4355.2006.

Vitone C (2019) Contaminated soils and remedial strategies: geotechnical systems between complexity, chaos and sustainability. *Environmental Geotechnics* **6(7)**: 431–433, https://doi.org/10.1680/jenge.2019.6.7.431.

Vitone C, Federico A, Puzrin AM *et al.* (2016) On the geotechnical characterisation of the polluted submarine sediments from Taranto. *Environmental Science and Pollution Research* **23(3)**: 12535–12553, https://doi.org/10.1007/s11356-016-6317-x.

Vitone C, Cotecchia F, Federico A and Viggiani G (2018) On the geomechanical characterisation of complexities in clays: experimental studies. *Italian Geotechnical Journal* **52(2)**: 7–29, https://doi.org/10.19199/2018.2.0557-1405.07.

Waldrop MM (1992) *Complexity: the Emerging Science at the Edge of Order and Chaos*. Touchstone, New York, NY, USA.

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

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

Weaver JE, Wang L, Francis L and Barlaz MA (2019) Systems and methods for studying microbial processes and communities in landfills. In *Understanding Terrestrial Microbial Communities* (Hurst CJ (ed.)). Springer, Cham, Switzerland, pp. 129–150.

WHO (World Health Organization) (2020a) *Coronavirus Disease (COVID-2019) Situation Report-73*. WHO, Geneva, Switzerland. See https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200402-sitrep-73-covid-19.pdf?sfvrsn=5ae25bc7_2 (accessed 30/04/2020).

WHO (2020b) *Global Research on Coronavirus Disease (COVID-19)*. WHO, Geneva, Switzerland. See https://www.who.int/emergencies/diseases/novel-coronavirus-2019/global-research-on-novel-coronavirus-2019-ncov (accessed 30/04/2020).

Wigginton KR, Ye Y and 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, https://doi.org/10.1039/C5EW00125K.

Windfeld ES and Brooks MS (2015) Medical waste management – a review. *Journal of Environmental Management* **163**: 98–108, https://doi.org/10.1016/j.jenvman.2015.08.013.

Woodbury AD and 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, https://doi.org/10.1029/1999wr900273.

Wu D, Huang XH, Sun JZ, Graham DW and Xie B (2017) Antibiotic resistance genes and associated microbial community conditions in aging landfill systems. *Environmental Science & Technology* **51(21)**: 12859–12867, https://doi.org/10.1021/acs.est.7b03797.

Wu HL, Jin F, Bo YL, Du YJ and 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, https://doi.org/10.1016/j.conbuildmat.2018.03.164.

Wu HL, Du YJ, Yu J, Yang YL and Li VC (2020) Hydraulic conductivity and self-healing performance of engineered cementitious composites exposed to acid mine drainage. *Science of the Total Environment* **716**: article 137095, https://doi.org/10.1016/j.scitotenv.2020.137095.

Xia WY, Du YJ, Li FS *et al.* (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, https://doi.org/10.1016/j.jhazmat.2019.02.031.

Xia WY, Du YJ, Li FS *et al.* (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, https://doi.org/10.1016/j.conbuildmat.2019.03.195.

Xiao B and 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 *et al.* (2020) Management of corona virus disease-19 (COVID-19): the Zhejiang experience. *Zhejiang Da Xue Xue Bao Yi Xue Ban* **49(1)**: 1–12, https://doi.org/10.3785/j.issn.1008-9292.2020.02.02 (in Chinese).

Yang YL, Reddy KR, Du YJ and Fan RD (2018) Short-term hydraulic conductivity and consolidation properties of soil–bentonite backfills exposed to CCR-impacted groundwater. *Journal of Geotechnical and Geoenvironmental Engineering* **144(6)**: 48–55, https://doi.org/10.1061/(asce)gt.1943-5606.0001877.

Ye M, Neuman SP and Meyer PD (2004) Maximum likelihood Bayesian averaging of spatial variability models in unsaturated fractured tuff. *Water Resources Research* **40**: article W05113, https://doi.org/10.1029/2003wr002557.

Yeh TCJ, Khaleel R and Carroll KC (2015) *Flow through Heterogeneous Geologic Media*. Cambridge University Press, Cambridge, UK.

Yu Z, He P, Shao L, Zhang H and 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, https://doi.org/10.1016/j.watres.2016.10.042.

Yu S, Wang X, Chen Z *et al.* (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, https://doi.org/10.1016/j.jhazmat.2016.09.009.

Zhan S, Yang Y, Shen Z *et al.* (2014) Efficient removal of pathogenic bacteria and viruses by multifunctional amine-modified magnetic nanoparticles. *Journal of Hazardous Materials* **274**: 115–123, https://doi.org/10.1016/j.jhazmat.2014.03.067.

Zhang D (2001) *Stochastic Methods for Flow in Porous Media: Coping with Uncertainties*. Academic Press, San Diego, CA, USA.

Zhang H, Nordin NA and Olson MS (2013) Evaluating the effects of variable water chemistry on bacterial transport during infiltration. *Journal of Contaminant Hydrology* **150**: 54–64, https://doi.org/10.1016/j.jconhyd.2013.04.003.

Zhang P, Wang K, Li Q, Wang J and Ling Y (2020) Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders – a review. *Journal of Cleaner Production* **258**: article 120896, https://doi.org/10.1016/j.jclepro.2020.120896.

Zhao B (2006) Transport of viruses in soil: an overview. *Acta Pedologica Sinica* **43(2)**: 306–313, https://doi.org/10.11766/trxb200503150221.

## How can you contribute?

To discuss this paper, please submit up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as a discussion in a future issue of the journal.