







# URBAN SUSTAINABILITY

In the face of climate change, expanding cities and limited resources, effective use of land and water infrastructure is critical to the sustainability of our metropolises



# ON SAFER AND SUSTAINABLE GROUND

The University's geotechnical researchers are global leaders in the theory and engineering of unsaturated soil mechanics, slope stability, mitigation of landslide risk, and risk assessment of multi-hazards

While residing in our rapidly expanding cities is often likened to living in a concrete jungle, few recognize that 99.99% of man-made structures are actually supported by natural geomaterials, such as soil and rocks. Unsaturated soils, covering most of the Earth's land surface, are one such type of geomaterial and, like other geomaterials, their behavior and properties are highly complex, since they are path-dependent (resembling our upbringing and history), stress-dependent, and strain-dependent. These soils are also prone to external loads, such as earthquakes, rainfall, and changes in temperature and humidity. Such loads can cause the soils to expand or contract and potentially collapse, making them hazardous to the natural and man-made structures they support. Understanding these intricate soils is therefore challenging but essential if we are to achieve sustainable development and enhance the mitigation of natural and human-induced disasters.



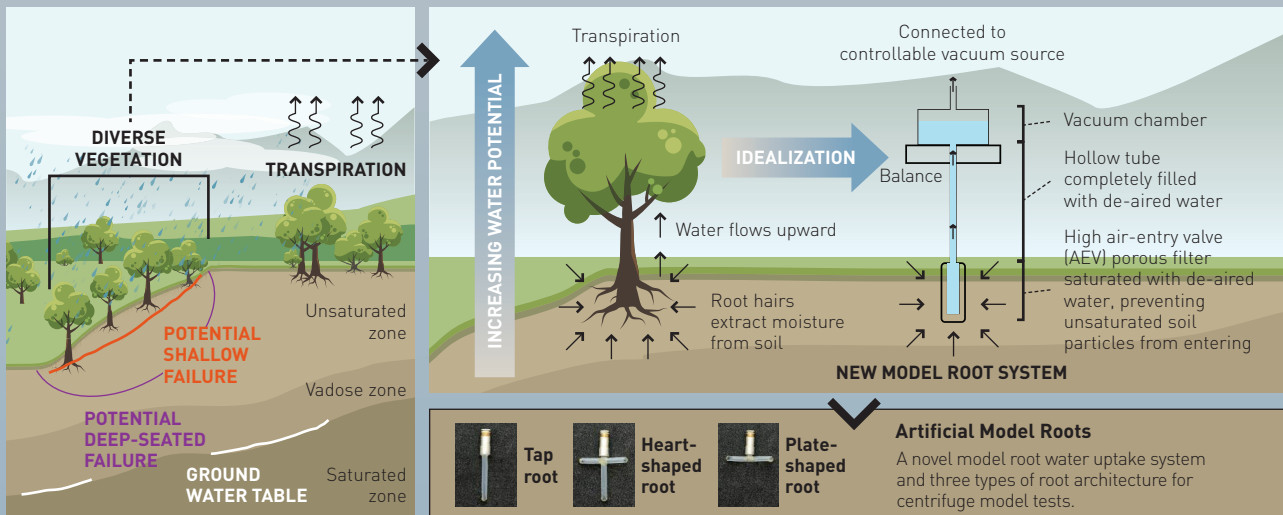
“Soils are highly complex and varied, just like people, and offer a cornucopia of knowledge for someone with a curious mind”

**PROF CHARLES WW NG**  
 CLP Holdings Professor of Sustainability,  
 Associate Vice-President for Research  
 and Graduate Studies,  
 President of the International Society for  
 Soil Mechanics and Geotechnical Engineering

## Getting to the Root of Unsaturated Soils

Over the past two decades, Prof Charles Ng has taken up the challenge posed by unsaturated soils. He has advanced fundamental knowledge and practice related to slope stability and maintenance, as well as debris flows, a type of fast-moving landslide. In Hong Kong alone, there are tens of thousands of man-made and natural slopes. Recognizing early that these geomaterials needed further exploration, Prof Ng established the unsaturated soil research group at HKUST in 1995 and started the first postgraduate courses on unsaturated soils in Asia the following year. They have gone on to develop a series of theoretical state-dependent elastoplastic frameworks for unsaturated soils, which have become the theoretical basis for experimental and further theoretical studies by researchers globally. Unlike previous

### Green Slope Engineering



The roots of plants grown on natural and man-made slopes offer an elegant solution to stabilize slopes. They help to provide both mechanical anchoring as well as soil suction via transpiration to reduce water infiltration, and increase shear resistance to potential failure.

theories of unsaturated soil mechanics, these trend-setting frameworks enable researchers and engineers to simulate interaction among cyclic mechanical, hydraulic (water content and suction), and thermal (temperature) behavior of unsaturated soils in different states and stress-, path-, and strain-dependency.

To verify this theoretical work, Prof Ng's research team has developed and patented novel experimental apparatuses, including a suction-controlled stress-controllable pressure plate extractor, and a temperature-controllable cyclic triaxial apparatus equipped with a novel double-cell total volume measuring system, known as the "HKUST Inner Cell". This has been licensed to a UK company and nearly 200 universities and research institutions worldwide have adopted the plate extractor and the HKUST Inner Cell, the latter of which is now among the standard measuring methods globally.

## Nature's Engineers

Based on such in-depth knowledge of the properties and behavior of unsaturated soils, Prof Ng and his team have gone on to make a series of innovative research contributions to slope stability and sustainability. One such area is soil-plant-atmospheric interactions and bioengineered live cover systems. The researchers discovered that not only do plant roots provide mechanical reinforcement, but more importantly, they also induce soil suction via transpiration (hydrological effects), increasing soil shear strength and reducing water infiltration in slopes and landfill covers. "Plants are intelligent natural 'engineers'," Prof Ng noted. "They can cost-effectively stabilize man-made structures and natural slopes, and contribute to the development of environmentally friendly and sustainable cities."

Through this and related discoveries, the team then developed and patented an innovative artificial model root system.

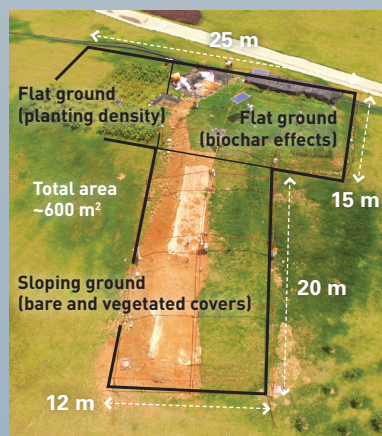
The new system used HKUST's world-class geotechnical centrifuge to simulate both the mechanical and hydrological (suction) effects of different types of root architecture and hence their impact on induced soil suction and slope stability.

The research group was the first to identify possible types of slope failure involving different types of root architecture. They also derived new analytical solutions to calculate plant-induced soil suction by different root architecture to predict the stability of vegetated soil slopes. With this understanding, the HKUST team could advise on the type of vegetation to plant to increase slope stability in what they called "green slope engineering". In addition, the researchers identified plant characteristics of geotechnical value. Through measuring the leaf area index, for example, engineers could estimate induced suction in the ground and hence analyze slope stability. The research was supported by two multidisciplinary Collaborative Research Fund projects in Hong Kong and a National Basic Research Program (973 project) in Mainland China.

## Eco-friendly Three-layer Landfill Cover

Hong Kong's landfills are filling up faster than expected. The amount of waste in the city's overflowing landfills has increased by 80% in the past 30 years, with a large percentage coming from the construction sector.

Based on advanced unsaturated soil mechanics, Prof Ng's research team has invented and patented a new environmentally friendly three-layer landfill cover system to protect the environment from gas emissions from



the landfill body and to minimize water infiltration into the waste after closure of a landfill. This type of landfill cover system has since been extended to use construction waste as cover materials. No artificial materials, such as geomembranes, are needed to minimize rainfall infiltration and gas emissions from the landfill. The elimination of artificial, non-environmentally friendly geomembranes can also prevent interface failure of a traditional landfill cover system.

Unlike traditional soil cover systems, the HKUST system is suitable for all weather conditions. It is self-regenerative, durable, and virtually maintenance free.

### Landfill Cover Composition



### Trial at Shenzhen, Xiaping landfill site

A schematic of the novel three-layer landfill cover system using recycled crushed concrete (above) and the field trial using recycled waste at the Xiaping landfill site in Shenzhen, China (left). Recycled crushed concrete is both practical and cost-effective, widening potential interest in both developing and developed countries.

## Mitigating Debris Flows with Multiple Flexible Barriers

In addition to green slope engineering initiatives, Prof Ng has now set out to add to global understanding of natural terrain landslides and mitigation measures through a cutting-edge investigation into the interaction between debris flows and multiple flexible barriers. Such barriers are especially useful solutions for densely-populated, hilly cities, for example Hong Kong, and for protecting inter-city infrastructure, such as roads and railways, across mountainous regions, for example Belt and Road initiative countries.

In 2016, Prof Ng brought together a multidisciplinary international research team to launch the five-year project, funded under the Theme-based



The world's largest man-made 160-meter long flume in Kunming, Mainland China. This facility has a channel width of six meters and will be able to simulate debris flow volumes of up to 500 m<sup>3</sup>.

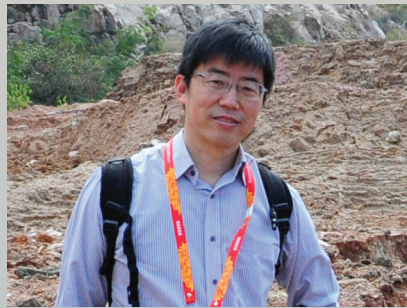


Research Scheme of the Hong Kong Research Grants Council. The project will develop the world's first scientifically based design guidelines for multiple flexible barriers. Flexible barriers can undergo large deformation, which is ideal for dissipating high-impact energy. Advantages of using multiple flexible barriers include their constructability, enabling designs to conform to complex mountainous terrain, their ability to blend into the natural surrounding environment, and lower cost.

Facilitating the research is a specially constructed world-leading 160-meter long flume facility in Kunming, Mainland China – part of a collaborative research effort between HKUST and the Chinese Academy of Sciences' Institute of Mountain Hazards and Environment. The flume will play a key role in revealing fundamental mechanisms of interaction between fast-moving landslides and multiple flexible barriers. To complement these large-scale flume tests, the researchers have developed the world's first geotechnical centrifuge model package which is capable of simulating flexible barriers for centrifuge testing. Work in the project's first year has already made an impact internationally, with Prof Ng and his team awarded a Telford Premium Prize in 2017 from the UK's Institution of Civil Engineers and an R.M. Quigley Award (Honourable Mention) by the Canadian Geotechnical Society for their papers on debris flows. The former prizes are awarded annually to work that is judged by peers to be of exceptional quality and benefit to those involved in civil engineering, construction, and materials science, while the latter awards are given to selected papers out of 296 published in the *Canadian Geotechnical Journal* in 2016.

Prof Ng has published some 250 articles in leading geotechnical journals and is the first author (with co-author Dr Bruce Menzies) of *Advanced Unsaturated Soil Mechanics and Engineering* (CRC Press 2007). Prof Ng was elected as the President of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) in September 2017, becoming the first in Greater China to hold this position in the 91 member societies, over its 80-year history.

## QUANTIFYING THE RISKS OF LANDSLIDES AND CHAIN REACTIONS



“ Geotechnical multi-risk assessment is an emerging area of focus and we are among the few institutions working on the science ”

**PROF LIMIN ZHANG**  
Professor of Civil and Environmental Engineering

Further innovative research in relation to mitigation of landslides and debris flows is ongoing at HKUST in the complementary area of quantitative multi-risk assessment, an emerging field in which the University's geotechnical engineering researchers are taking the lead locally and globally. When landslides and debris flows occur, one of the biggest risks is that they are not isolated events. The aftermath and chain reactions that can follow may in fact cause the greatest damage. As an example of the complexities facing researchers in assessing such hazards, Prof Limin Zhang cites the real-case scenario of a building impacted by the 2008 Sichuan earthquake, next by a landslide behind it, then by flooding and repeated debris flows. “Previously, as a civil engineer, vulnerability would be viewed as different levels of injury to a person or damage to a building. But when we face multi-hazards and their interactions, vulnerability becomes a very difficult issue,” he said.

Prof Zhang is a global expert on engineering risk assessment and

### Timeline of the Multi-hazards Caused by the Wenchuan Earthquake in Sichuan



#### BEICHUAN TOWN

Timeline of the multi-hazard scenarios that affected Beichuan following the Wenchuan earthquake

*Engineering Geology 180, 4-20 (2014)*



#### EPISODE 1

Wenchuan earthquake; collapse of buildings

#### EPISODE 2

Landslides; rock avalanches





Po Shan Road,  
Mid-Levels, Hong Kong,  
18 June 1972.

mitigation. In the past 10 years, he has focused on geotechnical multi-risk assessment. This builds out from traditional risk assessment and management to explore sequential or concurrent hazards and their interactions, issues not previously addressed in Hong Kong or around the world. Often working together with Prof Charles Ng on slope stability projects, Prof Zhang seeks to improve rational engineering decisions and management in relation to landslides and debris flows and in line with the needs of Hong Kong and Mainland China. A personal motivation to drive forward the field was fueled by the aforementioned earthquake in Sichuan, where he had previously lived and had relatives involved in the disaster.

### Novel Analytical Framework

The work of Prof Zhang's research team encompasses full-process multi-hazard numerical modeling, centrifuge modeling, remote sensing, data analytics utilizing Bayesian networks and Monte Carlo risk analysis simulations, development of risk management

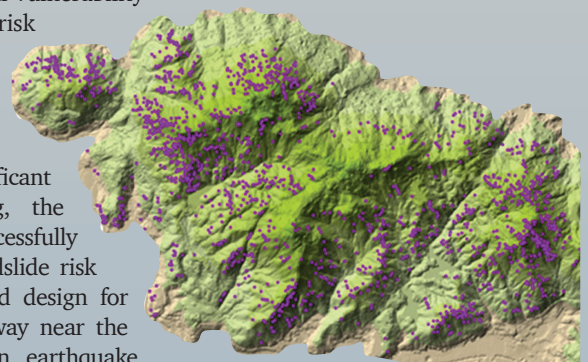
engineering frameworks, and the application of mitigation measures to different geotechnical and structural engineering scenarios.

To advance knowledge and practice, Prof Zhang and his team have established a novel multi-hazard risk analysis framework known as the HKUST five-step method: definition of scale and initiating events; identification of the multi-hazards and their interactions; interactions of elements at risk (human, property); multi-vulnerability assessment; and multi-risk assessment.

### Hazard Mitigation in Action

In a particularly significant project for Prof Zhang, the HKUST method was successfully utilized to provide a landslide risk assessment and risk-based design for rebuilding a major highway near the epicenter of the Sichuan earthquake. A landslide warning system was also installed to reduce risk once the highway began operating.

Locally, Prof Zhang and his team are investigating the potential impact of cascading landslide hazards on Hong Kong Island under extreme storms brought about by climate change. Supported by the Hong Kong Research Grants Council, the Collaborative Research Fund project seeks to develop a unique stress-testing framework to assess slope safety and system response, improvements and management strategies. Project collaborators include the Hong Kong



Western Hong Kong Island suffered 1,600 landslides between 1924 and 2009.

*Advancing Culture of Living with Landslides, 2, 17-32 (2017)*



JUNE 2008



SEPTEMBER 2008



JULY 2013

#### EPISODE 3

Flood from breaching of Tangjiashan Landslide Dam

#### EPISODE 4

Debris flow from landslides in Beichuan County

#### EPISODE 5

Change of river course; river scour

Old town ruins of Beichuan flooded due to rising riverbed; long-term evolution of hazards; future hazards



government's Geotechnical Engineering Office and Hong Kong Observatory.

In addition, Prof Zhang is working on expanding such stress-testing to cover Hong Kong's entire 1,100 square kilometers by building a high-resolution digital platform to simulate further low-probability, high-consequence risk scenarios, including severe flooding, landslides, debris flows and other intense hazards. He later hopes to extend this to the wider Guangdong - Hong Kong - Macao bay area, with its twin dangers of river flooding and storm surges.

### Boost for Decision-makers

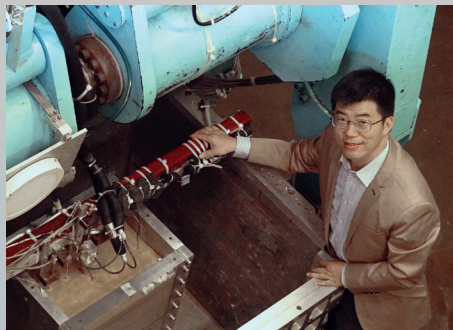
"As societies develop, public tolerance of damage decreases and is replaced by a general expectation of safety," Prof Zhang said. His research is thus in line with the greater need for social and political leaders to be accountable, should disaster strike, and such leaders' increasing reliance on quantitative risk-based assessment to explain the decisions made. In other words, a way to help everyone expect the unexpected through science.

Prof Zhang has published more than 200 international journal papers and is co-author of *Dam Failure Mechanisms and Risk Assessment* (Wiley 2016). He is also Editor-in-Chief of *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards* (Taylor & Francis).

## Centrifuge Generates Ground-shaking Impact



Prof Charles Ng's research group comprises students from 16 different nationalities.



Prof Limin Zhang uses the four-axis robotic manipulator installed on the centrifuge, capable of creating an elevated gravity field 150 times that of Earth's gravity for static model tests.

The HKUST Geotechnical Centrifuge Facility (GCF), set-up in 2001, was the first in the world to be equipped with a bi-axial shaking table for geotechnical earthquake engineering and a state-of-the-art four-axis robotic manipulator. The equipment gave HKUST researchers a competitive edge in carrying out advanced physical modeling of numerous engineering-related problems. The centrifuge has played a key role in attracting major research projects funded by large-scale grants such as Theme-based Research Scheme and Collaborative Research Fund, and advancing world-class geotechnical engineering research within the University and beyond. Prof Charles Ng was the Director since its official opening; under his 14-year leadership, the GCF remains a state-of-the-art leading centrifuge facility in the world. Prof Limin Zhang is the current Director.

## HKUST Five-phase Multi-hazard Risk Analysis

### PHASE I: DEFINITION

Define the source of risk, location and potential initiation (e.g. earthquake or rainfall). Then, investigate individual hazard lifecycles and the space scale that each hazard has evolved over its lifecycle.

### PHASE II: MULTI-HAZARD ASSESSMENT

Identify lead hazards (e.g. landslides or rock avalanches) and derived hazards (e.g. debris flows or river sedimentation) and investigate cascading effects and temporal and spatial evolution of hazards.

### PHASE III: INTERACTIONS AMONG ELEMENTS AT RISK

Identify elements that may be at risk and consider methods to resolve potential problems caused. For instance, consider rerouting traffic following a landslide that causes highway or road blockage.

### PHASE IV: MULTI-VULNERABILITY ASSESSMENT

Analyze interactions between vulnerabilities (e.g. human or structural vulnerabilities) and hazards.

### PHASE V: MULTI-RISK ASSESSMENT

Draw up assessment that calculates all possible risks from multiple hazards in a defined area, including overlapping and non-overlapping risks, risks from amplification and number of zones affected by root hazards, as well as overlapping hazards and derived hazards.



# SMART SOLUTIONS FOR WATER MANAGEMENT

Knowledge breakthroughs are building platforms for technologies that can assist eco-friendly water quality management, reveal problems in pipelines, and revolutionize wastewater treatment



Photo: Sam Tsang / South China Morning Post

Back in the swim after Hong Kong's major harbor cleanup. Hong Kong has a compact urban area yet also encompasses a 700-kilometer coastline and 1,700 square kilometers of diverse marine waters, which have served as a "big laboratory" for testing designs and solutions to mitigate many water pollution issues arising from the city's industrialization and population pressures.

## Fragrant Harbor 2.0

Cities are already home to 50% of the global population. Within two decades, this figure is expected to rise to 60%, or five billion people. Mitigating the impact of urban activities on the hydrosphere – oceans, seas, lakes, rivers, and other water bodies – and the monitoring and management of municipal water systems are major concerns for a sustainable future. Water pollution control in densely-populated coastal cities is a particularly challenging task that demands innovative technology, as the coastal waters in such urban settings typically have multiple beneficial uses.

Hong Kong has proved a significant location for water environmental engineers to contribute globally to understanding and technologies related

to the environmental hydraulics involved in such issues. The city's spectacular harbor (the name Hong Kong means "Fragrant Harbor" in Chinese) and many beautiful beaches have been a focus of attention, with the community goal of cleaning up the water pollution problems left over from its past role as the world's workshop from the 1960s to 1980s and sewage treatment needs of its rapidly rising population.

## Fathoming Buoyant Jets

For Prof Joseph Lee, the first Asia-based academic to receive the Hunter Rouse Hydraulic Engineering Award from the American Society of Civil Engineers, the theoretical understanding and mathematical modeling of the mixing of buoyant jets has been a core area over his 35 years of research.

Natural and polluting discharges in the environment exist as buoyant jets – wastewater effluents from cities and industry, thermal discharges from power stations, virus-laden plumes in the atmosphere, and hydraulic jets in civil engineering structures. The effluent discharge is mixed by the turbulent vortices in the environment, leading to a continuous and rapid reduction in pollutant concentration. Predictive modeling of buoyant jets provides a basis for environmental management and control, enabling impact and risk assessment, definition of mixing zones, the design of advanced effluent diffusion systems to meet water quality objectives, real time water quality management (for example, control of disinfection dosages), and public engagement for better understanding of the impact of infrastructure projects.



But it is a hugely complex task. How to forecast the mixing and turbulent vortices generated when, for example, a discharge of treated sewage is expelled into a tidal current or moving seawater (described as a buoyant jet because fresh water is lighter than seawater and the discharge has momentum)? And to predict turbulent buoyant shear flow not only for one buoyant jet but for hundreds of interacting buoyant jets?

## World-leading Predictive Modeling

In seeking to expand such understanding, Prof Lee has contributed a rigorous body of knowledge to the fluid mechanics of buoyant jets, publishing over 40 articles in leading international journals to date and authoring *Turbulent Jets and Plumes – A Lagrangian Approach* (Springer 2003).

Prof Lee and his team have also developed powerful tools to assist global research and practice in this area, including the JETLAG mathematical model to predict the initial mixing of an arbitrarily inclined buoyant jet in a current over a wide range of environmental conditions. From this, the researchers went on to develop VISJET computer ocean outfall modeling and visualization software.



“ How you formulate a problem is very important in engineering. We don’t make a problem more complicated than necessary. We take a complex issue and find a simple way of solving it effectively ”

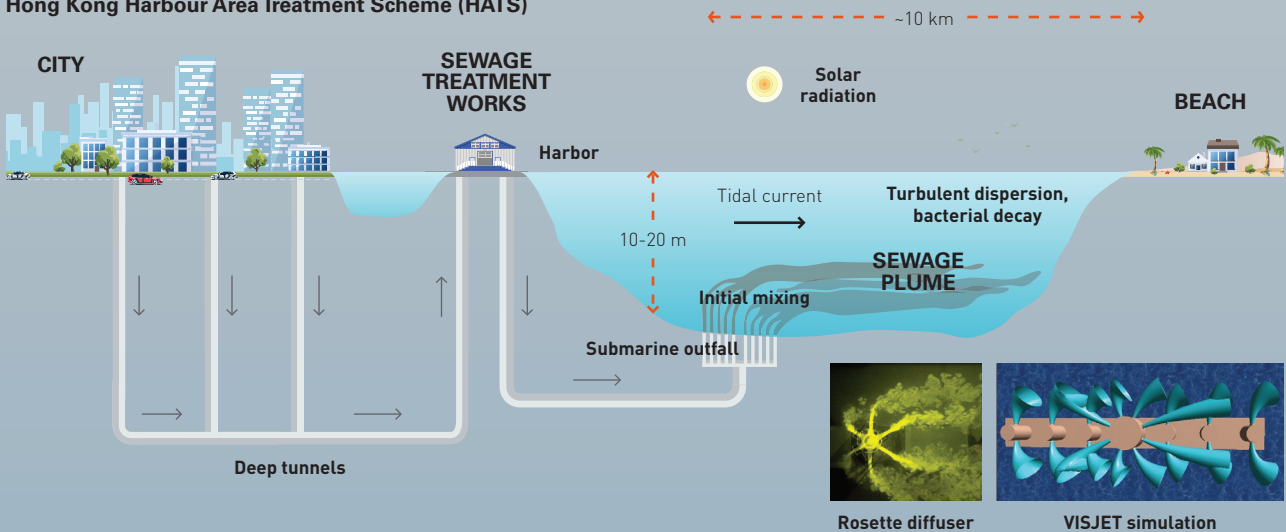
**PROF JOSEPH HUN-WEI LEE**  
Elman Family Professor of Engineering and Public Policy

JETLAG/VISJET, now in use in 50 countries, is the only model in the world that integrates accurate predictions of multiple jets with three-dimensional trajectories, including multiple plume merging and interaction, and advanced visualization technology. It is particularly suited for application in the heavily utilized shallow coastal waters in Asia. The related basic research received a prestigious 2010 State Scientific and Technological Progress Award (Second Class) from China's State Council.

## Treated Effluent, Chlorine Optimization

More recently, Prof Lee and his researchers have utilized their expert knowledge of buoyant jets to tackle a complex problem involving chlorination of treated effluent. Since 2010, the treated effluent at Hong Kong's Stonecutters Island Sewage Treatment Works, the world's largest chemically enhanced centralized primary treatment (CEPT) plant, has been disinfected by chlorination to reduce the bacterial (*E. coli*) level and protect the water quality of nearby bathing beaches. The plant serves a population of around 3.5 million, with a daily average sewage flow of 1.8 million

### Hong Kong Harbour Area Treatment Scheme (HATS)



Sewage from 3.5 million people is conveyed to Stonecutters Island Sewage Treatment Works, the largest of its kind in the world, via a 23.6 km-long deep tunnel system and is centrally treated by chemically enhanced primary treatment (CEPT). The treated effluent is discharged into the harbor in the form of multiple rosette buoyant jet groups from an ocean outfall. VISJET provides a realistic simulation for the trajectory and dilution of such a complex diffuser. Bacteria/pathogen loads are carried in the trapped sewage plume below the surface (in summer stratification) and transported by the tidal current while undergoing turbulent mixing and decay before arriving at a bathing beach.



cubic meters collected through a deep, 23.6 kilometer system of tunnels.

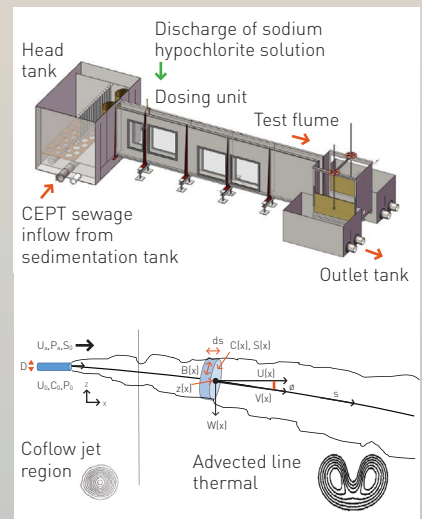
Inside the treatment plant, high concentration chlorine (10%) is injected into a “flowing river of treated sewage” in the form of multiple dense jets. While chlorine is an effective disinfectant for reducing pathogen levels, it is toxic to the marine environment and aquatic life. Actual operation shows that the chlorine concentrations fluctuate in a complex manner, and a good part of the chlorine is consumed by organics in the sewage rather than killing the pathogens. This is both costly and environmentally unfriendly.

To study the challenging problem, Prof Lee and his team designed and constructed a full-scale hydraulic model at the Stonecutters plant. “At the end of the day, the best theories have to face the test of reality. You can’t just

talk about principles,” he said. “That’s really what engineering is all about – integration of theory and practice.”

Findings have recently been reported in the *Journal of Environmental Engineering* in which Prof Lee outlines a theory for the mixing and chemical reaction of a chlorine jet with CEPT effluent, explains the puzzling chlorine consumption, and proposes various chlorine optimization strategies.

Prof Lee has served as expert consultant on numerous hydro-environmental projects and contributed to the design of several major urban environmental management and flood control infrastructure in Hong Kong, including the Tai Hang Tung Storage Scheme, Yuen Long Bypass Floodway, and the Hong Kong West Drainage Tunnel.



**Top:** The field-scale model at Stonecutters Island Sewage Treatment Works for studying chlorine dosage optimization in Hong Kong’s wastewater.

**Bottom:** Theoretical model of dense chlorine jets in sewage flow for dosage optimization.

## A Good Day to Go to the Beach?

The WATERMAN coastal water quality forecasting and management system, masterminded by Prof Lee, has provided a new way of dynamically coupling near and far field models using a Distributed Entrainment Sink Approach (DESA). This has enabled a robust and seamless simulation of the transport and fate of pollutants from the point of discharge to sensitive receivers (for example, bathing beaches) located kilometers away.

In practice, the WATERMAN system has become the first to predict coastal beach water quality in real time, with field validation, providing daily water quality forecasts for 16 Hong Kong beaches through the internet and a smartphone app. Based on statistical and 3D deterministic hydrodynamic and water quality models, it has achieved over 80% accuracy in forecasting compliance/exceedances with Hong Kong’s Water Quality Objectives.

In addition, WATERMAN enhanced communication, decision-making and emergency response through the development of a 3D environmental impact assessment system using hydro-environmental modeling and visualization technology; and took forward scientific management of fisheries through providing a prediction of the carrying capacity of Hong Kong’s 26 fish culture zones.

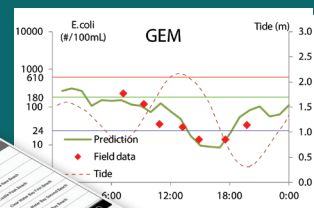
The project, funded by the Hong Kong Jockey Club Charities Trust, was awarded to Prof Lee in 2009 while at the University of Hong Kong. He continued to pursue the research after moving to HKUST in 2010, with a trial system becoming accessible to the public in 2011. Related publications have appeared in the *Journal of Fluid Mechanics*, *Water Research* and *Journal of Environmental Engineering*, among others.



Deep Water Bay



Big Wave Bay



The WATERMAN system provides a daily forecast of beach water quality, disseminated to the public through the internet and a smartphone app.



# IN THE PIPELINE



“  
 Ultrasound imaging is based on sending waves into a patient’s body and measuring the echoes. We want to do that with pipelines. We want to send acoustic waves in the fluid in pipes, capture the echoes, and use them to diagnose the health of the pipe system  
 ”

**PROF MOHAMED GHIDAOU**  
 Chinese Estates Professor of Engineering

Beneath the streets of Hong Kong lie over 7,500 kilometers of water pipes. In the US, there are more than 1.5 million kilometers. What is pressing for the sustainability of urban lifestyles and future development is that these immense labyrinths of pipelines in cities around the world are often aging and inefficient. Leaks and bursts contribute to business losses, social disruption, and require expensive renewal strategies – if they can be afforded. (The Hong Kong government recently completed a 15-year project replacing 3,000 kilometers of pipes at a cost of over HK\$23 billion.) Globally, a staggering 30%-40% of piped urban water is wasted annually due to system deficiencies and World Bank estimates place the cost of water loss at US\$15 billion each year.

## Pressure Wave Potential

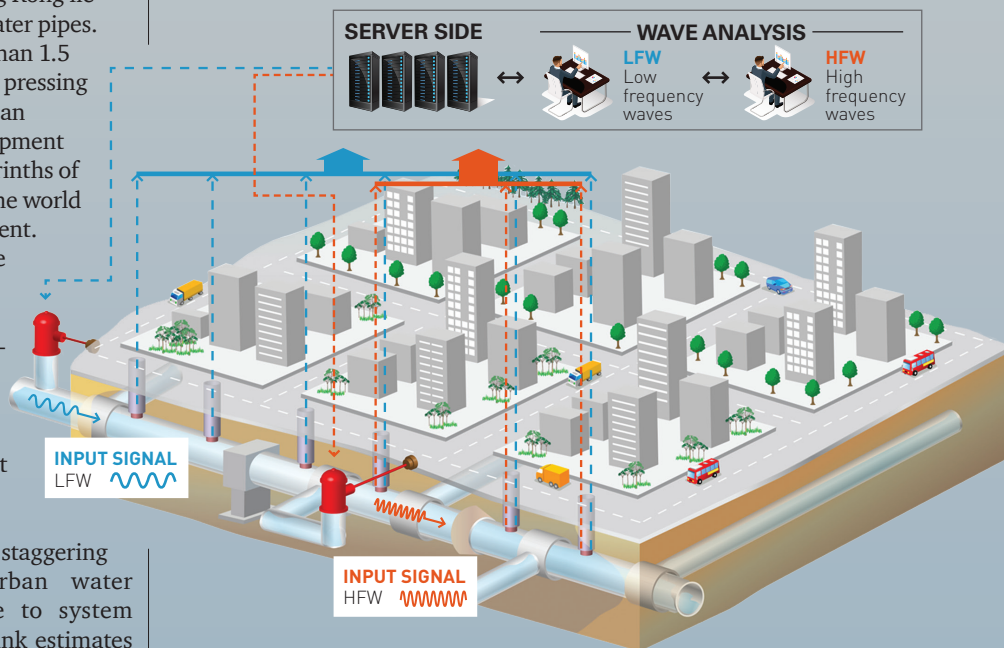
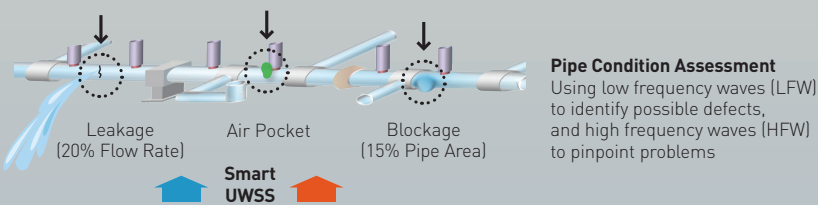
Prof Mohamed Ghidaoui, an expert in hydraulics and fluid mechanics, is now

tackling these issues through visionary research with the potential to take urban water supply systems to the next level of efficiency, cost-effectiveness, and sustainability. Prof Ghidaoui is seeking to harness understanding of the propagation and reflection of pressure waves in pipelines to build a “smart”, pioneering real-time diagnostic management platform. The “smart” platform will utilize sensors in pipes and wave-based techniques and technologies to allow engineers to continuously monitor the health of underground water systems and rapidly pinpoint and anticipate pipeline problems, in a non-disruptive and non-intrusive manner.

In water systems, the simple action of starting a pump, or opening and closing a valve, causes pressure waves. Traditionally, these waves have been

seen as detrimental to conduits and most engineering efforts to date have focused on ways to mitigate or suppress them. However, from his accumulated research findings over the past 20 years, Prof Ghidaoui is focusing on the beneficial outcome of pressure waves – pipeline diagnostics. In a similar way to a doctor conducting an ultrasound scan in a clinic, waves could be used as tools to “image” conduits and, from analysis of the resulting data, find and characterize system defects, such as leaks, blockages and pipe deterioration. Being fast (pressure waves travel at one kilometer per second) and non-intrusive (waves can be sent to sample a large area of pipeline from just one location), such tools would also facilitate system-wide diagnosis and be applicable to most faults.

### Smart Urban Water Supply Systems (Smart UWSS) Using Waves as Diagnostic Tools



The bottom plate depicts a section of a pipe system under roads and buildings; its state and condition are unknown. Pressure waves are generated in the pipes by a pump, valve, or piezo-electric transducer and travel rapidly through the pipelines at a speed of one kilometer per second. These pressure waves are picked up by sensors in the pipes, and the data is wirelessly transmitted in real-time to the base-stations, where it is transformed into sharp images showing the state of the system, providing valuable information for analysis of pipe defects e.g. blockages, leaks, and weak pipes.



## Fluid Mechanics Meets Signal Processing

Conventional pipeline diagnostic systems possess certain limitations, with good reason – pipes are buried deep underground, out of sight and difficult to access. Current technology only covers a short range (200 meters or less), produces low-resolution data, targets specific faults, and is unable to forecast problems. These critical limitations call for a new diagnostic paradigm for water supply network monitoring and fault detection. However, establishing a proactive "wave" diagnostic platform is no simple feat. It will involve complex physics and mathematics, a highly dynamic environment encompassing a "web of pipes", numerous active devices and flow controls, noise from turbulence, traffic, construction activities, and random flow demands.

Overcoming these issues is now the focus of a groundbreaking inter-

disciplinary Theme-based Research project, led by Prof Ghidaoui and supported by Hong Kong Research Grants Council. The Smart Urban Water Supply Systems initiative is a pioneering undertaking involving an international group of leading researchers from Hong Kong, Mainland China, North America, Europe, and New Zealand, together with the Hong Kong government's Water Supplies Department. The team brings together engineering experts in hydraulics and fluid mechanics, signal processing and wireless communications and structural mechanics as well as mathematicians.

The researchers are currently studying sensing of actively generated fluid waves traveling at high speed in pipelines and how to use the electronically captured wave echoes to "image" and diagnose the pipes. Theories are being evaluated in the lab at HKUST and in

field studies in Hong Kong's urban area. A pilot-scale demonstration experimental test bed has also been developed in Beacon Hill, Kowloon, Hong Kong. Findings can crucially contribute to the sustainable development of Hong Kong through water conservation and locally developed innovation and technology. However, the focus is not solely on Hong Kong but on a system that will work anywhere in the world.

Prof Ghidaoui has published in leading journals such as the *Journal of Hydraulic Engineering*, *Journal of Fluid Mechanics*, and *Journal of Hydraulic Research*. In 2007, he received the Arthur Thomas Ippen Award, the highest honor presented by the International Association for Hydro-Environment Engineering and Research (IAHR). He now serves as Editor-in-Chief for the *Journal of Hydraulic Research*, IAHR.

## FROM SLUDGE TO SANI

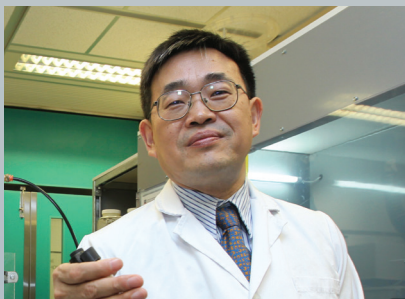
Sewage sludge is a growing worldwide problem, as established cities deal with expanding populations and new urban areas spring up in developing economies requiring efficient treatment for sanitation. Conventional plants utilize biological processes that convert around 60% of the organic carbon in sewage to carbon dioxide and the remainder to sewage sludge. Such sludge is then disposed of in landfills or incinerated, contributing to greenhouse gas emissions and using up energy.

### Seawater Change

Prof Guanghao Chen and his team have been working on the problem since 2004, studying the connections between seawater, sulfate and sludge, leading to the transformational SANI municipal wastewater treatment process that is generating opportunities for a cleaner environment through innovative ways to deal with "dirty water".



SANI launched a full-scale trial at Hong Kong's Shatin Sewage Treatment Works in the summer of 2014.



“Urban sustainability to me means the three Rs: reduce, recover, and reuse”

#### PROF GUANGHAO CHEN

Chair Professor of Civil and Environmental Engineering

SANI stands for Sulfate reduction Autotrophic denitrification and Nitrification Integrated process, or "sludge killer" in Chinese. The original platform stems from a happy confluence: Hong Kong's use of seawater for flushing as an alternative to fresh water (it is one of the few places in the world to do so and is the result of a historical initiative to mitigate the city's lack of water

resources); and Prof Chen's investigations into the potential of sulfate to reduce the sewage sludge produced from conventional wastewater treatments.

### Three-wheel Cycle

The traditional two-wheel organic oxidation and nitrification biochemical reaction using the integrated carbon and nitrogen cycle employs microbes to convert organic pollutants into carbon dioxide and clean up sewage. However, such microbes grow rapidly through this process, creating large amounts of unwanted sludge as a by-product. The novel three-wheel integrated cycle proposed by Prof Chen employed slow-growing sulfate-reducing bacteria and sulfate in seawater together with nitrification to oxidize and eliminate pollutants. The method proved highly viable in lab and pilot testing, reducing oxygen needed for organic matter removal and minimizing sludge generation. From 2007 to 2010, a pilot test plant at Tung Chung Sewage Pumping Station in Hong Kong showed a 90% sludge reduction at a capacity of 10 cubic meters of sewage per day.

In 2013, with the assistance of Hong Kong government departments,



Prof Chen set up a 1,000 cubic meter sewage demonstration plant that resulted in significant conclusions: 60%-70% reduction in biological sludge, 20% reduction in energy required for treatment and requiring 40%-50% of the space for treatment. Optimization is currently underway to make the process even more compact and effective at reducing sludge, and to ultimately achieve a more energy-saving system.

The revolutionary treatment process has brought 19 patents and resulted in over 70 publications and five international awards, including three from the eminent International Water Association. The technology drew interest from the UNESCO-IHE Institute for Water Education, leading to a three-year study involving Prof Chen, the European Union, and a SANI pilot demonstration plant in Cuba.

The study, completed successfully in June 2017, highlighted ways to mitigate water scarcity on the island through leading-edge urban water management systems. SANI has also attracted attention from major national and international water and environmental companies.

## Recovery Discovery

Exciting extensions to the fundamental SANI platform are now moving forward. Costly materials that normally cannot be synthesized on an industrial scale can be recovered from SANI sludge and two of Prof Chen's students will set up a company to take forward their innovative sludge-to-resource technology that can help realize production of sulfated polysaccharides, a high-valued raw material used in the food and pharmacy industries. The technology won the exhibition award at the 7<sup>th</sup>

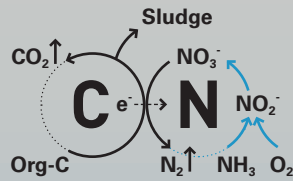
Annual HKUST One Million Dollar Entrepreneurship Competition in 2017.

Prof Chen and his research team are also exploring the recovery of phosphorus from human urine. Phosphorus, which is rapidly being exhausted, is an important element for food production through its use in fertilizers. In ongoing research, the team has shown the potential for seawater-catalyzed urine phosphate recovery in a process that adds seawater to hydrolyzed urine, leading to the formation of a valuable phosphorus-containing fertilizer (struvite precipitates). Related research has appeared in *Water Research*.

"Now we have SANI, our goal is to continuously lead the way for space-saving, energy-efficient wastewater treatment and resource recovery through the testing and application of new technologies," Prof Chen said.

### Carbon Cycle – Nitrogen Cycle

Conventional Activated Sludge (CAS) process using the two-wheel organic oxidation and nitrification biochemical reactions.



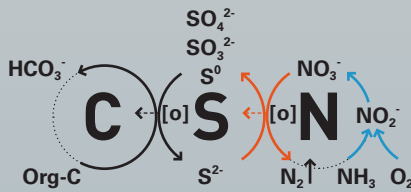
Sewage treatment area



Biological sludge \*

### Carbon Cycle – Sulfur Cycle – Nitrogen Cycle

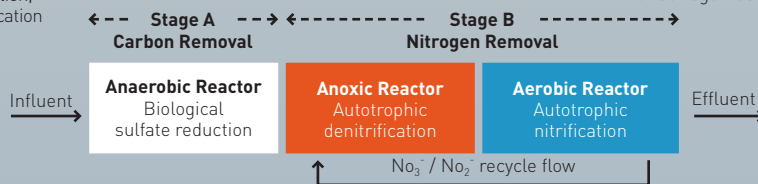
The novel three-wheel integrated cycle proposed by Prof Chen - anaerobic sulfate reduction, sulfide oxidation and autotrophic denitrification, and nitrification process.



40%-50% reduction of space needed for sewage treatment



60%-70% reduction in biological sludge



*Water Research*, 100, 496-507 (2016)

\*Photo: Sustainable Sanitation Alliance

In the first reactor (anaerobic), sulfate is reduced to sulfide by sulfate-reducing bacteria while organic carbon is oxidized to carbon dioxide (which dissolves as bicarbonate). In the second reactor (anoxic), sulfide is subsequently oxidized back to sulfate by sulfur-oxidizing bacteria while nitrate is autotrophically reduced to nitrogen gas. In the third reactor (aerobic), ammonia is oxidized to nitrate by the nitrifiers. All three functional bacteria are slow growers, i.e. they have very low yields and hence produce minimal sludge.

## Fresh Links

In 2015, HKUST gained approval from the Ministry of Science and Technology of China to establish a Hong Kong Branch of Chinese National Engineering Research Center (CNERC) for Control and Treatment of Heavy Metal Pollution. The Center is led by Prof Guanghao Chen and encourages collaboration between Hong Kong, Mainland China, and overseas water experts.

The focus is on optimization of water systems and the development of new technologies for adoption by industry to enhance smart urban water and wastewater management, linking to Prof Mohamed Ghidaoui's and Prof Joseph Lee's work on waves in pipelines and turbulent mixing in rivers and oceans respectively. "Our main target is the use of different types of water – saline, brackish water – as alternative water resources to reduce the use of the increasingly precious resource of fresh water," Prof Chen said. "And to develop smarter urban systems in terms of quality assurance and monitoring."