DEPARTMENT OF CIVIL & MINERAL ENGINEERING

RESEARCH HANDBOOK

Civil & Mineral Engineering
UNIVERSITY OF TORONTO

2023 - 2024

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INTRODUCTION

From the deep underground to the world's tallest structures, you can find examples of how U of T Civil and Mineral Engineering research is addressing the need for innovative solutions to society's needs.

Our dedicated students, staff and professors are pursuing exciting research in Structural, Transportation, Environmental, Building and Mining/ Geotechnical engineering. This research is informed by extensive collaboration and interaction with industry and government partners.

Our facilities and breadth of research expertise are among the best in the world, offering great opportunities for involvement in groundbreaking research. In this publication you will discover a wide range of urgent problems that our society needs to address, and an even wider range of innovations we're creating to meet them.

Marianne Hatzopoulou

Chair, Department of Civil & Mineral Engineering

LAND ACKNOWLEDGMENT

We wish to acknowledge this land on which the University of Toronto operates. For thousands of years it has been the traditional land of the Huron-Wendat, the Seneca, and the Mississaugas of the Credit. Today, this meeting place is still the home to many Indigenous people from across Turtle Island and we are grateful to have the opportunity to work on this land.

STRUCTURAL ENGINEERING RESEARCH

ADVANCED SIMULATION METHODS FOR STRUCTURES SUBJECTED TO EARTHQUAKE, WIND, OR FIRE LOADS

Prof. Oh-Sung Kwon

THE PROBLEM

With the current levels of modelling technologies and computing power, increasingly complex and realistic models of structures are being developed and refined, primarily in single modelling packages. However, the scientific and engineering community has not yet achieved complete models that can capture the entire response of complex structural systems in order to fully assess their performance under various extreme loading conditions, such as earthquakes, strong winds, and fire. How can we take advantage of multiple tools with different capabilities to capture the realistic behaviour of the structural systems that cannot be easily handled in a single simulation tool?

THE APPROACH

Professor Kwon and his research group are advancing the multi-platform and hybrid simulation techniques that allow decomposition of a complex structure or a large-scale structure-media system (e.g., structure-soil) into multiple substructures or subsystems. Each substructure or subsystem can be either numerically modelled on a computer or experimentally tested in the laboratory considering its interaction with the other substructures/subsystems.

To facilitate the implementation of such integrated simulation method in existing analysis software and testing facilities, a generalized numerical/experimental simulation framework, termed as the University of Toronto Simulation Framework (UT-SIM), has been developed at the University of Toronto. The framework is characterized by a standardized data exchange format and network communication protocol that has seamlessly integrated several software packages, such as Abaqus, LS-DYNA, S-Frame, VecTor program suite, and OpenSees. It can also be used for any custom-built program with source code access written in Matlab, Python, C++. Fortran, or LabVIEW. In addition, various testing facilities such as the uniaxial shake tables, the multi-axial shake table, the shell element tester at the University of Toronto as well as equipment in other institutions can be used for hybrid simulations through the Network Interface for Controllers (NICON).

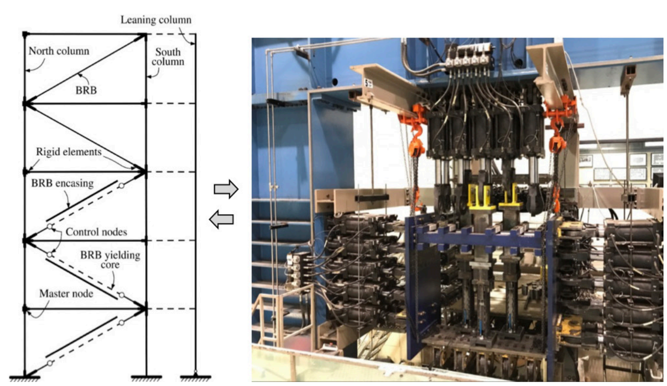
Although the UT-SIM framework was initially developed for performance assessment of structures under earthquakes, it is being further extended by the research group to other loading scenarios such as wind and fire by developing new integrated simulation algorithms and experimental testing techniques.

THE IMPACT

The UT-SIM framework has fostered extensive collaboration between the University of Toronto and the academic institutions and industry partners in Canada, the United States, the United Kingdom, Greece, China, Italy, South Korea, India, and many others towards developing the next generation of numerical and hybrid numerical-physical simulation strategies and applying these advanced methods to solve real engineering problems which are rarely seen from previous simulations.

WHAT'S NEXT?

The proposed UT-SIM framework is an open concept that is available to the entire research community in order to invite researchers and practicing engineers to contribute to the development of the UT-SIM framework by integrating their own research developments. The further enhanced framework will lead to more resilient infrastructure systems against natural and human-made disasters.



A BRB frame where three BRB cores are physically modelled in the Shell Element Tester

STRUCTURAL ENGINEERING RESEARCH

SUSTAINABLE CONCRETE STRUCTURES IN MARINE ENVIRONMENT

Prof. Shamim A. Sheikh

THE PROBLEM

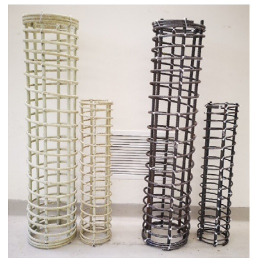
The use of de-icing salts in northern environments and rising and warmer sea levels aggressively corrode steel in reinforced concrete infrastructure resulting in shorter life span in coastal areas. Viability of glass fibre-reinforced polymers (GFRP) as replacement of steel in concrete structures is evaluated for longevity in a replicated laboratory marine environment. The research also addresses potential degradation mechanisms in the GFRP bars?

Coastal Structure, California, U.S.A.

THE APPROACH

Professor Sheikh's students have developed accelerated conditioning mechanism to simulate coastal environment to evaluate behaviour of reinforced members for long-term performance.

For a comparative study, identical steel- and GFRP-reinforced concrete columns are exposed to the same simulated coastal environment to evaluate their strength and ductility retention and overall structural integrity over time. To replicate the long-term exposure in the field and warming trends due to climate change, seawater solution will be heated in the 50 to 60˚C range with the goal of simulating 25 to 75 years of service life. The coastal environment conditioning in the lab will include wetting and drying cycles to replicate events such as tidal and seasonal changes. The second phase of this work will investigate basalt FRP bars.



GFRP and steel cages for columns

Conditioning tanks in the lab

THE IMPACT

This study will provide an understanding of the long-term behavior of FRP reinforced concrete marine structures in changing climate conditions with the goal of developing procedures for the design of structures for a service life of 50 to 100 years. The results will provide design guidelines for bridges and other coastal structures to engineering industry that should result in safer, sustainable, and economical reinforced concrete construction.

WHAT'S NEXT?

The second phase of this research will include newer materials such as basalt FRP. In addition, a comparative study of stainless steel reinforced concrete components will also be carried out. Data collected from the experiments will be used to develop design guidelines and code provisions that will directly benefit industry and coastal authorities.

STRUCTURAL ENGINEERING RESEARCH

SUSTAINABLE CONCRETE STRUCTURES UNDER CHANGING CLIMATE TREND

Prof. Shamim A. Sheikh

THE PROBLEM

Cost of steel corrosion to the economy is about three per cent of world's GDP every year of which over 16 per cent is related to infrastructure. In reinforced concrete, replacement of steel with fiber reinforced polymers (FRP) as reinforcement both for upgrade of existing structures and building of new ones offers opportunities to address this problem while presenting new challenges for engineers and researchers especially with the changing climate trends.

THE APPROACH

Professor Sheikh and his students are adopting an accelerated conditioning approach to investigate the material and structural behaviour in the laboratories and analytically model the long-term performance of structures under extreme climate conditions, fires and more frequent and increased freeze-thaw cycles.

Ongoing work in the Structural Testing Facilities involves an overarching experimental program investigating material level specimens and large structural components with internal or external FRP reinforcement. The material (glass, carbon and basalt FRP) behaviour is being investigated under temperatures up to 400˚C and up to 500˚C freeze-thaw cycles. The structural program is designed to determine the impact of elevated service temperatures and extreme temperature cycles on the structural components while subjecting them to a variety of realistic loading conditions including earthquake.

This work has been underway in collaboration with The Natural Sciences and Engineering Research Council of Canada (NSERC) Centres of Excellence, National Research Council of Canada (NRC), a number of industrial partners, University of British Columbia and Zhengzhou University.

THE IMPACT

The Ontario Ministry of Transportation has made an extensive use of the structural upgrade techniques developed as part of this ongoing research and called it a "Milestone in Life Extension of Structures." Results from this research have been implemented in the current CSA design codes from which industry and government are directly able to benefit.

WHAT'S NEXT?

Data collected from the field and experiments will be used to develop procedures to evaluate behaviour of structures subjected to extreme loads and climate conditions. This will lead to safer design of structures and improved code provisions for evaluating existing structrues and design of new structures.

Specimens under conditioning at elevated temperatures

STRUCTURAL ENGINEERING RESEARCH

SENSORS, STRUCTURES AND DECISIONS

Prof. Fae Azhari

STRUCTURAL HEALTH MONITORING

Bridges, pipelines, wind turbines and many other structures are susceptible to deficiencies due to different loading and environmental conditions such as corrosion, material aging, fatigue, and the coupling effects with extreme hazards. These structures, when damaged or deteriorated, no longer meet the required standards and need to be repaired and rehabilitated or even rebuilt. These procedures can be very costly and time consuming if damage or deterioration is not detected in a timely manner. The purpose of Structural Health Monitoring (SHM) is to accurately monitor the behaviour of structures, constantly assessing their performance and providing continuous data on their current conditions. Similar to the way a doctor would point out when an organ is malfunctioning in a patient's body during regular check-ups, an SHM system is able to diagnose and locate any anomalies in the structure. In the event of damage, deterioration or abnormal conditions, the engineer will be notified so appropriate measures can be taken. Since this notification happens at a very early stage, the remedial procedure will usually be timely and cost effective.

RESEARCH AVENUES

My work focuses on adapting existing technologies and methods to create novel solutions for SHM and prognosis. The goal is to address some of the gaps in the succession of tasks from sensor development to implementation and decision analytics. More specifically, we focus on the following two research avenues:

- Conducting meticulous laboratory and field experiments to produce high-quality data that can be used to answer two critical questions; "Is this the right sensing system for our intended purpose?" and "Have we developed and characterized the sensing system in the right way?"

- Developing decision-making frameworks that use probabilistic models to translate large amounts of collected data into efficient remedial management strategies.

One upcoming research project involves using cement-based sensors for spatial sensing of bridge decks. Unlike monitoring systems in the engineering world, which are often discrete in time and space, sensory organs in the bio-world are integrated within bodies and provide continuous information. We will use this bio-inspiration to develop SHM systems that provide diagnostic maps of strains, cracks, and corrosion of concrete structures. Smart (self-sensing) cement-based composites are ideal materials for this application because they are electrically conductive and their physical and mechanical properties are similar to those of the host structure.

STRUCTURAL ENGINEERING RESEARCH

RESILIENCE OF STRUCTURES

Prof. Constantin Christopoulos, Prof. Jeffrey Packer

THE PROBLEM

Earthquakes, wind storms and terrorist attacks can place structures under extreme forces without warning. Current structural designs allow for extensive damage to occur as long as collapse is prevented. How can we move to a better model of structures that are inspectable, repairable, and upgradeable more quickly and economically?

THE APPROACH

Professors Christopoulos and Packer work with the interdisciplinary Centre for Resilience of Critical Infrastructure and the recently renovated Structural Testing Facility to perform large tests under real-time loading conditions. Equipment unique in Canada that can apply more than one million lbs. of load and dynamic actuators that can apply 500,000 lbs. moving at one metre per second allow them to test their newly invented experimental systems in full-scale.

Other ongoing research includes investigations of welds in steel hollow structural connections, shock load tests on steel and glass, and blast testing using a simulator that is unique in Canada. Field blast research in remote locations allows researchers to design specimens in full scale and load test them to failure using TNT and ANFO explosions.

THE IMPACT

Collaborations with North American universities, the ROSE School (Pavia, Italy) and Technion - Israel Institute of Technology (Haifa, Israel) allow students to gain international exposure. Recent graduates have helped develop new damping mechanisms and cast steel connections that are being applied around the world through spinoff company CastConnex. These innovations result in more cost-effective designs to mitigate the vibrations caused by seismic events and severe winds, enhancing the comfort and safety of occupants in tall buildings.

The Program into Protection Against the Effects of Energetic Loads is developing innovative wall panel connectors, failure prediction models for glass façades and steel hollow structural section members that can better resist blast loads.

WHAT’S NEXT?

The various technologies being developed in our labs will see widespread use in Canada and around the world. These advanced technologies will become more readily available to practicing engineers, making our infrastructure as a whole more resilient. Eventually, design codes will move away from today’s damage-tolerant models.

STRUCTURAL ENGINEERING RESEARCH

TUBULAR STEEL STRUCTURES

Prof. Jeffrey Packer

THE PROBLEM

One area of particular growth in the field of structural engineering is that of tubular steel structures. However, design know-how has not kept up with the imagination of architects and the thirst for free-form designs. The structural reliability of many concepts and arrangements needs to be continually demonstrated, to ensure levels of safety that are acceptable to the public.

THE APPROACH

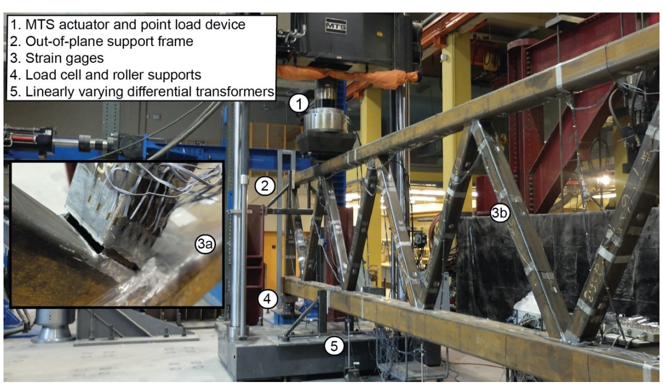
Experimental (from small- to large-scale), numerical and analytical studies are performed into the behaviour and design of hollow structural section (HSS) members, connections, and bolted and welded joints. Materials investigated range from hot-formed to cold-formed steel products, steel-concrete and steel-FRP composites, steel castings and diverse fasteners. Loading conditions include quasi-static, fatigue, impact, seismic and blast, using leading-edge dynamic loading equipment in the U of T Structural Testing Facilities or field-research methodologies. Technology transfer to industry and into codes of practice is emphasized, through scholarly publications and presentations, software, patents, trade associations, specialized consulting services and tailored courses (including the graduate course, CIV1175).

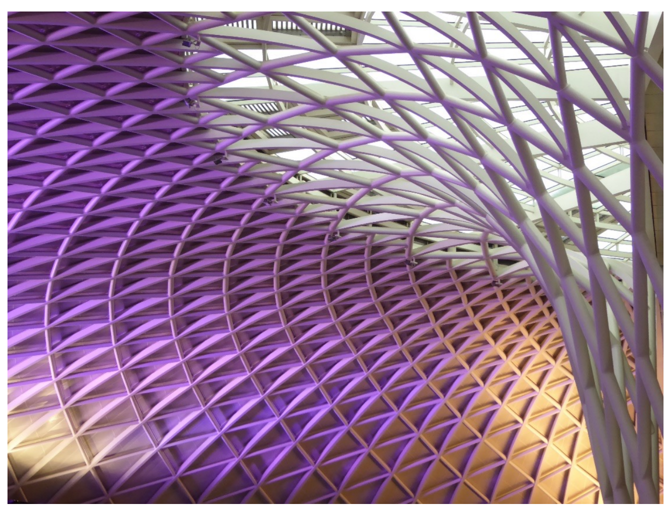
THE IMPACT

The University of Toronto is widely recognized as one of the world's foremost knowledge hubs for Tubular Steel Structures. The expertise of this centre is accessed by the Steel Tube Institute (STI), the International Committee for the Development and Study of Tubular Structures (CIDECT), the International Institute of Welding (IIW), the American Institute of Steel Construction (AISC), the Canadian Institute of Steel Construction (CISC) and steel tube producers. Research, oriented towards practical applications, is performed at U of T to advance design recommendations for international and national standards and specifications, as well as developing new and innovative structural systems.

WHAT'S NEXT?

Researchers in the research group at U of T will find their conclusions incorporated into future editions of design standards, such as CSA S16, CSA W59, AISC 360, AWS D1.1 and ISO 14346. Experience and skills obtained by researchers are directly transferable to industry practice.





STRUCTURAL ENGINEERING RESEARCH

NONLINEAR STRUCTURAL ANALYSIS OF REINFORCED CONCRETE STRUCTURES

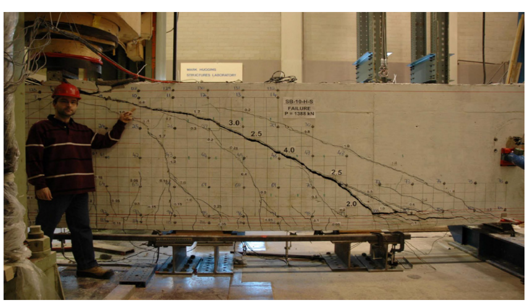
Prof. Evan Bentz

THE PROBLEM

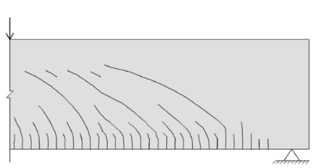
In order to better design structures to resist earthquakes or higher environmental loads, such as hurricanes induced by climate change, it is important that engineers have a good understanding of how their structures will behave when subjected to these actions. Current design methods assume the structure will show linear elastic behaviour. While this is simplification for design, it neglects many aspects of structural behaviour that current computers are able to model easily. The problem is that for sufficiently complex structures, it can be a challenge to find the right balance of simplicity and generality.

THE APPROACH

Standard Finite Element Analysis methods are based on the assumption that the strains inside each element follow a particular pattern based on what are called “shape functions”. While these are excellent for general problems, using them for cracked reinforced concrete analyses is actually a mistake and decoupling the flexural and axial load response from the shear response allows a better solution to be obtained with a surprisingly small number of elements. The figure shows the predicted crack diagram of a simply supported beam compared to the observed cracks.



Model of 2D slice of a building using the new finite elements



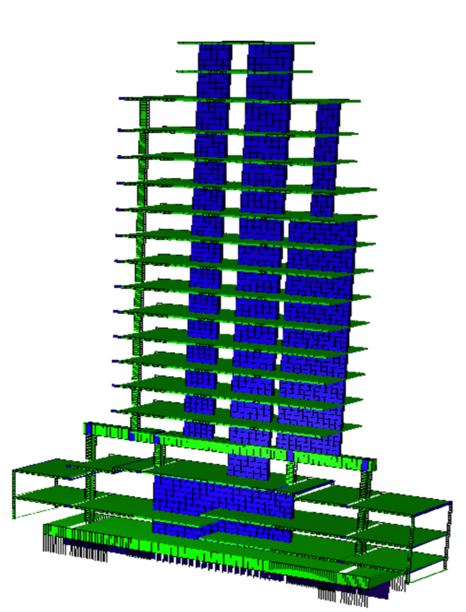
Predicted crack pattern from analysis with 48 finite elements

THE IMPACT

Using these new, efficient finite elements, it becomes possible to analyze a full building in the amount of time it used to take to analyze a single beam. This will allow better design against earthquakes and wind forces and allow better design to be considered. Current design methods often neglect the impact of creep, shrinkage, member elongation, cracking, yielding, and cyclic loads. This level of approximation is appropriate for existing designs as the safety factors are high enough to accommodate this. But for structures designed to use less materials for a lower amount of embodied carbon, it may not be appropriate to neglect all of these issues anymore.

WHAT’S NEXT?

The analysis method works well for tension, compression and shear driven problems. It is being developed now to include clamping stresses near areas of complex geometry. This should allow better modelling of flexural ductility levels, as well as including the detrimental impact of shear. The method is also being extended to 3D to include slabs, torsion and to allow the full modelling of existing, complex designs.



Model of 2D slice of a building using the new finite elements

STRUCTURAL ENGINEERING RESEARCH

TOWARD DIGITALLY-FABRICATED MASS TIMBER STRUCTURES

Prof. Aryan Rezaei Rad

THE PROBLEM

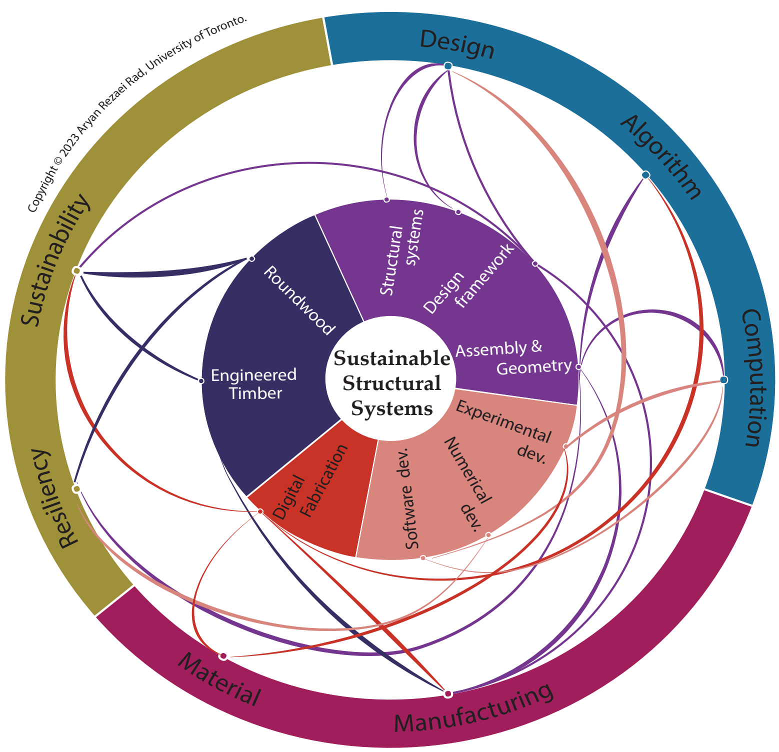
The key question in our research is how to use digital fabrication techniques and computational approaches to design affordable, resilient, and eco-friendly buildings using mass timber.

THE APPROACH

Professor Rad's research is at the interface of multi-scale experimental and computational methods to develop new design frameworks for sustainable, high-performance structural systems. Our research is supported by the knowledge emerging from advanced manufacturing. We use an integrated design approach and human-machine interactive design with construction materials that have low embodied carbon. We research the design of assemblies and machine-produced structural components to build engineering structures with optimized typology, representing a fundamentally new way of designing mass timber buildings.

THE IMPACT

Our output strategy prioritizes developing design frameworks for building components at scale. We employ well-defined data exchange between domain-specific toolchains using open-source computational environments along with multi-scale experimental methods. Our research efforts aim to raise the paradigm-shifting and risk-taking threshold in the Architecture, Engineering, and Construction (AEC) sector with a contribution that can be easily disseminated and distilled into industry-focused innovations with immediate application in engineering practice.



TRANSPORTATION ENGINEERING RESEARCH

TRANSPORTATION DEMAND MODELLING AND SIMULATION

Prof. Khandker Nurul Habib

THE PROBLEM

Over 80 per cent of Canadians live in urban environments. Cost-effective, high-performance transportation systems are critical to the economic productivity, environmental sustainability, and quality of life of Canadian and global cities. Detailed understanding of urban travel behaviour is fundamental to the planning, design, and operation of sustainable, resilient, efficient transportation systems. The problem is that we need to understand not only the current problems/issues, but also how these may project into the future.

THE APPROACH

I develop mathematical, behavioural models to ascertain how human beings currently move from one location to another and the multiple ways in which people respond to changes to the urban infrastructure. Using activity-based travel modelling, Me and my students are able to assess the choices people make and why they make them. When big questions emerge, like whether or not to construct a new subway line, these models can be used to make evidence-based decisions.

I used agent-based microsimulation approaches to model daily travel demand to transportation and land-use (urban forms) interactions. Mathematical models are embedded into such a simulation framework that provides tractability of responses to any transportation investments and policy implementations.

THE IMPACT

Professor Habib's research team has developed CUSTOM-GTASim, a fully operational agent-and activity-based microsimulation model system of daily activity and travel demands that allows the movement of every agent through the space and transportation network. It is operational and can allow transportation demand analysis, environmental impacts, and transportation energy demand modelling. Unlike rule-based simulation techniques, it uses microeconomic theory-based choice models to model peoples' preferences. It is proven to replicate both constraint and latent demands. His research team also developed a state-of-the-art travel survey tool, TRAISI, that allows the designing of various types of travel surveys, including stated preference surveys and integration with a smartphone app or Google timelines data.

WHAT'S NEXT?

New, "big data" concerning travel behaviour and application of "machine learning" and "artificial intelligence" are providing the basis for even more sophisticated and more policy-sensitive modelling methods that can further improve urban transportation decision-making and, thereby, the quality of life in our urban regions.

TRANSPORTATION ENGINEERING RESEARCH

AGENT-BASED MICROSIMULATION OF URBAN SYSTEMS

Prof. Eric Miller

THE PROBLEM

Cities are "problems in organized complexity," driven by the individual and collective behaviours of their populations. The transportation system is a particularly important component of our cities, enabling the day-to-day movement of people and goods fundamental to urban life. The behaviour of this system in terms of travel flows, performance levels, impacts (pollution, safety, etc.) is an emergent outcome of the individual decisions of millions of "agents" – people and firms – living their daily lives within the city. The design of an equitable, efficient and effective transportation system requires understanding this complex interplay of people and their activities.

THE APPROACH

To model at the fundamental level of each individual person and household within an urban area. This supports the implementation of behaviourally sound, context-sensitive models of human decision-making within complex urban settings that enable policy-makers to understand how people will respond to a wide range of transportation and urban design policies, so that the benefits and costs of these policies can be assessed.

Professor Miller is a pioneer in the development and application of agent-based microsimulation model systems in high-performance computing environments for the implementation of activity-based travel models in operational practice. This includes the development of integrated transportation – land use models that permit the analysis of the two-way interaction between transportation systems, housing markets, population demographics, regional economic development and urban form.

THE IMPACT

Professor Miller's research team has developed GTAModel V4, a fully operational agent-and activity-based microsimulation model system of daily activity and travel behaviour, which is in operational use by the City of Toronto and almost all other municipalities within the Greater Toronto Area (GTA). It is used by GTA planning agencies to assess the impacts of major transportation infrastructure investments, transit fare policies, road pricing options, and transportation accessibility equity issues, among other policy issues.

GTAModel is also being implemented for operational planning use in Montreal, Halifax and Monterrey, Mexico. Its transferability to other global urban regions has also been tested in Australia (Melbourne and Sydney), Chile (Temuco), China (Changzhou), Finland (Helsinki), Paraguay (Asunción), South Africa (Cape Town) and the United Kingdom (London).

WHAT'S NEXT?

New technologies and technology-enabled services are profoundly disrupting the transportation field, while the COVID-19 pandemic has also forced significant changes in our attitudes towards commuting, transit usage, etc. Agent-based microsimulation models provide an ideal framework for exploring these many changes in travel behaviour in the coming years. At the same time, new sources of "big data" and advanced data science methods for analyzing such data will enable us to observe and understand travel behaviour in new ways that will support further evolution of our modelling capabilities.

TRANSPORTATION ENGINEERING RESEARCH

DEEP LEARNING-BASED TRANSIT MANAGEMENT STRATEGIES

Prof. Baher Abdulhai, Prof. Amer Shalaby

THE PROBLEM

Uncontrolled flows of people in crowded transit hubs and transit vehicles along congested routes diminish the capacity and efficiency of our transit systems. Can we develop smarter transit control strategies to better control passenger, train, and bus flows within major hubs and transit corridors?

THE APPROACH

Professors Shalaby and Abdulhai collaborative work focuses on developing smart control strategies using the state-of-the-art deep reinforcement learning techniques to achieve optimal performance of existing transit systems. This research aims to assist agencies such as the Toronto Transit Commission, the Ministry of Transportation of Ontario, the City of Toronto, and Metrolinx. This research focuses on developing strategies for optimal and integrated control of passenger, train, and bus flows through major hubs and connecting lines. The ultimate objective is to minimize the total user delay and maximize the system throughput. The proposed strategies are being tested on a simulation model of Canada's busiest transit hub, Union Station, in Toronto. Shalaby and Abdulhai also collaborate on developing innovative control strategies that would make surface transit vehicles faster and more reliable. These algorithms include developing coordinated transit signal priority algorithms using deep reinforcement learning. They are also reimagining our streets by proposing new dynamic transit lanes to replace traditional dedicated transit lanes for better road utilization.

THE IMPACT

The simulation results from this research show significant improvements in the overall traveller delays and system reliability for both transit riders and motorists. The results indicate better road utilization, shorter travel times, and more reliable service.

WHAT'S NEXT?

This work has been tested on simulation models of the busiest transit hubs and routes in Canada's largest city, Toronto. Implementing the proposed control strategies is expected to improve the performance of the entire transportation system in the city.

TRANSPORTATION ENGINEERING RESEARCH

TRAFFIC-I WITH AI

Prof. Baher Abdulhai

THE PROBLEM

Traffic congestion is escalating worldwide. With increasing populations, urbanization and vibrant economies, demand for people and goods mobility is higher than ever before. In 2023, Toronto ranked seventh-worst city in the world in terms of traffic congestion (INRIX 2023). Congestion occurs when and where dynamic demand surpasses road capacity. This recurs daily during peak periods and is further exacerbated in the presence of non-recurring accidents or adverse weather. The high demand will not fit in the limited existing capacity, but capacity itself also deteriorates during peak demand by some 10-20% because of congestion-induced turbulence, right when we need capacity the most, which doubles delays.

THE APPROACH

Abdulhai's research at the U of T Intelligent Transportation Systems Centre (ITS Centre) focuses on finding intelligent solutions to traffic congestion problems using Artificial Intelligence (AI). The core overarching concept is to adaptively pace demand into the road network without overwhelming the road network and causing capacity loss and exacerbated congestion. Pacing means 'if you want to arrive faster, slow down, pace yourself, because rushing clogs the system' to the detriment of all. Traffic AI is applied to manage both demand and supply. Some examples include:
1. time varying congestion pricing to influence the pacing of demand into the network and flatten the peak,
2. Adaptively control traffic lights, freeway onramps, dynamic speeds on freeways, and dynamic headways for Autonomous Vehicles (AVs) using Reinforcement Learning. The methods are developed and testbed in extensive simulation and digital twins of real traffic networks in Toronto, Canada.

THE IMPACT

AI-based intelligent control of traffic, such as adaptive traffic signal and adaptive ramp control based on our in-house research, can reduce delays (e.g. at intersections) and reduce travel times (e.g. on freeways) by ~30-50%, without building new infrastructure.

WHAT'S NEXT?

We believe our current control systems are road worthy and ready to be deployed in the real world on a few intersections and on a freeway in the Toronto area. While we continue theoretical research which is boundless, the culmination of 25 years of research is taking it to the streets. A pilot deployment will involve optimizing traffic detection methods that best suit the AI control systems, communication infrastructure, data exchange, edge computing for decentralized deployment etc. A field deployment will be the first and long-awaited real-world implementation of state-of-the-art AI traffic control in a major city in Canada. It will showcase collaboration between Canada's top university and traffic authorities in Canada is largest city on cutting edge solutions to congestion, bridging the gap between academic innovation and real-world implementation on city streets.

TRANSPORTATION ENGINEERING RESEARCH

CITY LOGISTICS FOR THE URBAN ECONOMY

Prof. Matthew Roorda

THE PROBLEM

Over 80 per cent of Canadians live in urban areas, and these urban areas are where the majority of goods are produced and consumed. Goods are transported by all modes including trucks, rail, cargo cycles and walkers. They move from factories to warehouses and intermodal yards, on roadways and rail lines that frequently operate at or near full capacity. Traffic congestion impedes the smooth movement of freight vehicles and impacts negatively the emissions produced while delivering the cargo. Amid changes in e-commerce operations (e.g., same-day delivery), trade agreements, transportation vehicle technology, and the changing fortunes of different sectors of the economy, there is a need for data and improved analysis tools to understand the effects on freight flows, supply chains, infrastructure needs and regional economies across Canada. Most recently, the COVID-19 pandemic has led to increased recognition of the importance of supply chain resilience and has resulted in rapid and possibly permanent shifts toward e-commerce and home delivery.

THE APPROACH

City Logistics for the Urban Economy (CLUE), a university/industry/government partnership, built upon relationships formed by the Smart Freight Centre (SFC), a multi-university collaboration. CLUE conducts research that assesses demand for goods, alternative ways of moving freight in urban areas, the impacts of goods movement on communities and the environment, and the effectiveness of policies and initiatives designed to reduce these impacts. CLUE consists of 24 projects organized into four themes:

1) freight data collection and data science applications,
2) logistics network design for new e-commerce delivery models,
3) city logistic pilot studies,
4) safety, environment, and, labor force dynamics.

THE IMPACT

Among these 24 research projects, some focus on methodological research, while others focus on real-world pilot testing of urban freight initiatives in collaboration with the public and private sectors. The first pilot is a partnership between the University of Toronto, Purolator, and the City of Toronto, which has resulted in the installation of a micro-hub for last-mile delivery by e-cargo cycles. The second pilot assesses the impacts of Off-Peak Deliveries (OPD) undertaken by Loblaw Inc. and Walmart Canada, which found that the average speed of the trips made in off-peak hours during the six-month pilot was 18 per cent faster than those that happened in regular daytime hours, and 10 per cent fewer greenhouse gas emissions and air pollutants such as CO, NOx, PM10, and PM2.5. For more information on the pilots, refer to the following links:

Pilot 1: https://www.utoronto.ca/news/u-t-campus-used-living-laboratory-study-sustainable-last-mile-package-deliveries

Pilot 2: https://peelregion.ca/transportation/goods-movement/_media/pdf/pilot-off-peak-delivery-program-report.pdf

WHAT'S NEXT?

The CLUE team is continuing to work on a variety of city logistics projects, including the design of crowd-shipping programs, the assessment of automation technologies for goods movement, the social justice implications of freight emissions, labour force dynamics in the freight and logistics industry, truck driver training methods, and others.

TRANSPORTATION ENGINEERING RESEARCH

THE CENTRE FOR AUTOMATED AND TRANSFORMATIVE TECHNOLOGIES (CATTS)

Prof. Baher Abdulhai, Prof, Khandker Nurul Habib,
Prof. Marianne Hatzopoulou, Prof. Matthew Roorda, Prof. Amer Shalaby

THE PROBLEM

Canadian cities need to analyze, rationalize, and optimize their existing transportation resources and infrastructure to improve the efficiency of all modes of travel. Transformative technologies and mobility services such as automated driving, electric vehicles, connected vehicles, ride-hailing and ride-sharing have the potential to offer significant improvements if used properly but may also deteriorate the system if used improperly. This research guides positive transformation using new technology and mobility services to minimize the need for brute force infrastructure expansion.

THE APPROACH

The Centre for Automated and Transformative Transportation (CATTS) was launched in July 2017 at the University of Toronto, to study how disruptive transportation technologies and services (e.g. driving automation, pervasive connectivity, on-demand transit, E-hailing and E-sharing, innovative transit first-mile last-mile services, and robotic delivery of goods) will affect our cities positively or negatively. This research program is designed to provide a solid evidencebased knowledge that can be used by decisionmakers at all levels of government to channel transportation transformative technologies towards positive outcomes. The outcomes of this research are sets of analyses, case study evaluations, and analytical tools that model the performance and impacts of such technologies on human socioeconomic behaviour and transportation system performance. Such tools are to support government policies and initiatives that ensure that our cities are more sustainable economically, socially, and environmentally. This is accomplished through the performance of five distinct yet related tracks, covering a broad scope of transportation systems planning and management, including travel demand forecasting, traffic control and management, transit management, freight operations and demand modelling, and sustainability.

THE IMPACT

This initiative focusses on policy and infrastructure analysis of local applications in the Greater Toronto and Hamilton Area (GTHA). Such methods and their applications at the local level can be quickly and easily adapted to be usable in other Canadian Cities. The research addresses traveller behaviour considering new transportation technology and services and assesses whether existing infrastructure can handle the changes in demand. The research also creates tools for improving the use of existing infrastructure and capacities through exploiting Vehicle Automation and Communication Systems (VACS). Special attention is paid to next-generation transit, integrated mobility, and curb space in busy downtown cores. Further, this project provides tools that will improve the quality of life of Canadians by the sustainability of smart cities in the era of automated and transformative technologies.

WHAT'S NEXT?

The CATTS is finalizing Phase I of its research in 2023 that focused on building the analytical foundation of CAV impacts on the transportation infrastructure. CATTS is planning for a Phase II, piloting some of the promising systems from Phase I, while continuing fundamental research on all tracks.

TRANSPORTATION ENGINEERING RESEARCH

URBANSCANNER: REAL-TIME AIR POLLUTION MONITORING AND MAPPING

Prof. Marianne Hatzopoulou

THE PROBLEM

Accurate mapping of air pollution is crucial for assessing population exposure and informing city planning. The recent development of low-cost air pollution sensors has opened new ways of collecting and predicting air pollution in urban areas.

THE APPROACH

The Transportation and Air Quality (TRAQ) research group, led by Prof. Hatzopoulou at the University of Toronto has partnered with Scentroid, a Toronto based company that has been developing sensor-based systems for urban air pollution monitoring. The UrbanScanner platform includes a range of air pollution sensors in addition to a GPS, camera, lidar, as well as temperature and relative humidity sensors. Images are used to extract important features of urban neighborhoods. These features are then linked to the air pollution data and used to train a range of machine learning models that can make air quality predictions across the city.

THE IMPACT

This research helps cities identify hot spots for air pollution across the day, and examine the spatial distribution of air pollution across neighborhoods, and the environmental justice implications of air pollution exposure.

WHAT'S NEXT?

The team is partnering with fleet operators to install smaller versions of the UrbanScanner platform on the rooftops of delivery vehicles, making them air pollution sensors.

ENVIRONMENTAL ENGINEERING RESEARCH

HIGH TECHNOLOGY SOLUTIONS FOR CLEANER, SAFER DRINKING WATER

Prof. Robert Andrews, Prof. Susan Andrews, Prof. Ronald Hofmann

THE PROBLEM

Canadians enjoy some of the safest drinking water in the world, but contaminants like pharmaceutical chemicals constantly threaten to disrupt conventional treatment methods. Municipalities and industries are under pressure to meet the highest safety standards while reducing cost, energy and waste. Public confidence in municipal water systems is vital to the maintenance of sustainable water infrastructure.

THE APPROACH

The Drinking Water Research Group is home to one of the most comprehensive water research laboratories in Canada, including $3 million worth of analytical equipment that allows detection and monitoring of emerging contaminants. The Drinking Water Research Group conducts full-scale pilot research with industry partners, governments and agencies around the world on issues like microbial risk assessment, photolysis based advanced oxidation, granular activated carbon, ferrate treatment, and computer applications for improved water quality with lower environmental and economic costs. The ability to move seamlessly from lab test to pilot project to full-scale application gives Drinking Water Research Group researchers the advanced tools necessary to stay at the forefront of water treatment research.

THE IMPACT

Research completed in the Drinking Water Research Group has had a profound and direct impact on government codes and standards committees. Examples of impact range from water treatment methods used in Greater Toronto Area facilities, to recommendations to the Ontario Ministry of the Environment and Climate Change, to a two-year advanced sensor technology project in Singapore. Knowledge created in this research group directly influences public health, medicine and policies for the protection of water resources.

WHAT'S NEXT?

Advanced membrane technology is one example of a greener water treatment technology being developed to use fewer chemicals and less energy to deliver safer, higher quality water. The Drinking Water Research Group is working on a variety of advanced water treatment technologies suitable for resource-limited regions.

ENVIRONMENTAL ENGINEERING RESEARCH

RESTORING AND PROTECTING THE QUALITY OF AQUATIC RESOURCES

Prof. Brent Sleep, Prof. Elodie Passeport

THE PROBLEM

Anthropogenic activities have negative impacts on surface water and groundwater, such as industrial contamination of groundwater from hydrocarbon, chlorinated solvent spills and car-derived chemicals and rubber microplastics in urban stormwater. These can severely impact ecosystem and human health. How can new technology aid in recovery programs?

THE APPROACH

Professors Sleep and Passeport conduct hybrid research with laboratory experimentation, field studies and computer modelling to simulate the fate and transport of organic chemicals in the subsurface and surface aquatic environments. They also develop methods for restoration and protection of the environment.

Professor Sleep and his students are working on a variety of in situ subsurface remediation methods including thermal remediation, chemical oxidation, chemical reduction and bioremediation. They are also investigating the mechanisms that control the movement of pathogens in soils and fractured rock. Much of their work occurs at the intersection of hydrogeology, chemistry, microbiology and mathematics.

Professor Passeport is developing analytical tools based on stable isotopes to study the behavior of organic chemicals in surface water environments such as rivers, lakes and contaminated groundwater. Professor Passeport and her students are also developing different designs for Green Infrastructure, such as constructed wetlands and bioretention cells, to enhance their natural ability at reducing pollution. This includes investigating the chemical reaction mechanisms that govern the elimination of dissolved contaminants due to the action of light and bacteria, and the trapping of solids such as microplastics.

THE IMPACT

Industrial partners use the knowledge developed here to better assess risk factors when contaminants enter a site and to develop comprehensive remediation schemes that can more fully address environmental and health requirements. Professors Sleep, Passeport and their teams are working with industry and environmental consultants to transfer the knowledge needed to make decisions about appropriate environmental remediation technologies for a broad range of problems.

WHAT'S NEXT?

Professors Sleep and Passeport will continue to work with their research groups on the advancement of innovative remediation technologies, particularly on the development of coupled remediation processes.

ENVIRONMENTAL ENGINEERING RESEARCH

WHAT INFRASTRUCTURE SHOULD WE BUILD? HOW SHOULD WE BUILD IT?

Prof. Shoshanna Saxe

THE PROBLEM

Collectively, the world is expected to invest nearly $100 trillion USD in infrastructure by 2040 to meet societal demands for shelter, transportation, energy and commerce. There is thus a critical need for sustainable approaches to building and repairing infrastructure that will not devastate the planet through voracious use of primary resources (e.g. construction materials) and land (e.g. conversion of forests to suburbs). Infrastructure projects have impacts well beyond their stated primary purpose: they consume significant amounts of natural resources and change how we live, work and move. Infrastructure is further slow to build and long-lasting, magnifying the importance of getting infrastructure development 'right'. As key players in planning, designing, constructing and commissioning infrastructure, engineers have a special responsibility to improve the myriad ways infrastructure interacts with our natural and social systems.

The big question of my research is what infrastructure should we build? And once we have decided on a project how should we build it? Our population is growing and we need to reduce overall environmental pollution (reduce greenhouse gas emissions). Together that means our per capita emissions need to go down fast.

THE APPROACH

One stream of my current research is focusing on understanding material use in construction at the project, neighbourhood and city scale. Materials use drives environmental pollution, it also drives construction cost. How can we use building, neighbourhood and city form to reduce the materials we need? I am taking a bottom up approach, meaning that in my group we are studying as many specific projects as possible to build up to the material use in an entire city. The data is spatially disaggregated and purpose specific so we can ask questions about, where in the city are materials used? On what projects? For what parts of buildings? What forms are more sustainable?

THE IMPACT

Overall this work will inform both the practice of civil engineering design/construction and policy making (building codes, green standards, zoning). The goal is to come up with ways to deliver high quality infrastructure (e.g. a nice place to live) with less primary material use. The big impact goal is to reduce/slow climate change and do our part to save the planet.

WHAT'S NEXT?

We recently launched the Centre for the Sustainable Built Environment which will identify actionable pathways to build the infrastructure we need within climate limits. The centre is doing research quantifying how much new construction is needed, the GHG budget for construction, and form, structural design and material design pathways to build more with less.

ENVIRONMENTAL ENGINEERING RESEARCH

ADAPTIVE PLANNING OF LARGE WATER-ENERGY-FOOD INFRASTRUCTURE IN A CHANGING CLIMATE

Prof. Mohammed Basheer

THE PROBLEM

Water, energy, and food systems are inherently interlinked. For instance, rivers and lakes provide water for crop cultivation, hydropower, and cooling thermal plants; energy is used for water treatment and distribution and food processing; and food residuals can be used for bioenergy. These interlinkages are becoming stronger due to increasing demands for and changing supply of water, energy, and food resources because of population growth, economic development, and climate change. With the socio-economic and environmental uncertainties of climate change, fixed infrastructure development plans are no longer viable. Infrastructure development and management plans should be inherently adaptable as climate change unfolds and more information becomes available about its environmental and socio-economic impacts. Also, planning, designing, and operating large water-energy-food infrastructure should bring various relevant sectors and actors to the table to maximize benefits and balance costs. But how can we design such plans given the intersectoral complexities and climate uncertainties?

THE IMPACT

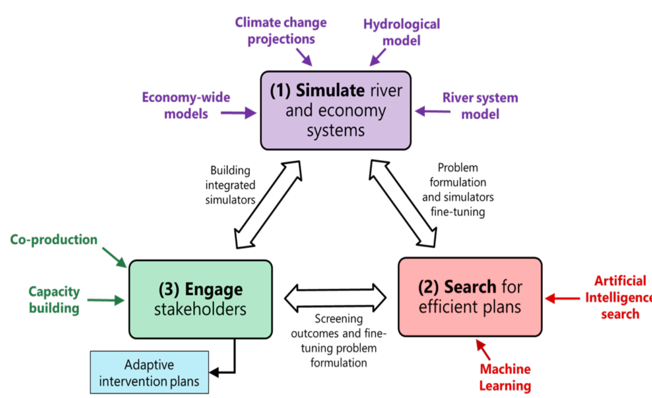
As countries and regions globally are developing infrastructure investment and management plans to ensure resilience to future uncertainties, the tools and methods developed by Professor Basheer's group can help create actionable adaptive plans for large water-energy-food infrastructure (e.g., dams and irrigation projects). In Canada, Hydropower, Conservation, and Water Authorities, among others, can use and benefit from the tools and methods for planning.

WHAT'S NEXT?

The group will continue to develop simulation models with enhanced representation of complex operations and interlinkages in water-energy-food systems, utilize state-of-the-art Artificial Intelligence techniques for enhanced computational efficiency, and improve the representation of human actions in biophysical systems by integrating economic and agent-based models.

THE APPROACH

Professor Basheer's group uses a three-step approach to tackle adaptive infrastructure planning: (1) Simulate, (2) Search, and (3) Engage. In the "Simulate" step, computer simulation models are developed to capture the complex dynamics of water-energy-food infrastructure and systems under various climate change scenarios. In the "Search" step, computer simulation models are connected to advanced Artificial Intelligence Search Algorithms to design efficient, adaptive infrastructure development and management plans. We typically perform this search process using the large-scale computational resources of The Digital Research Alliance of Canada to enable assessing thousands of plans. In the "Engage" step, Professor Basheer's group actively interacts with stakeholders and decision-makers to co-produce simulation models and deliberate the plans that come out of the Artificial Intelligence Search Process. These three steps are done iteratively in varying orders, depending needs.



BUILDING ENGINEERING RESEARCH

BUILDING RETROFITS: IMPROVING ENERGY USE AND INDOOR ENVIRONMENTAL QUALITY FOR OCCUPANTS

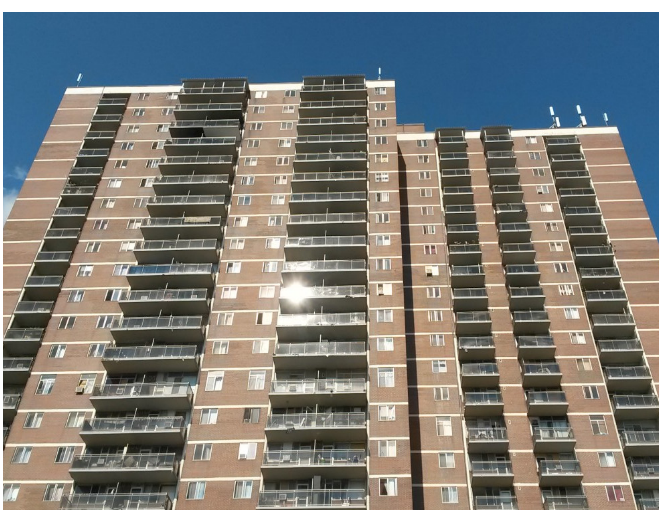
Prof. Marianne Touchie

THE PROBLEM

Most of the buildings that will exist in 2050 are already built. Given our aggressive greenhouse gas emission reduction targets, improving building energy performance through new construction alone is simply not going to cut it. We urgently need to retrofit our existing buildings to reduce the 17% of Canada's emissions they are responsible for. However, retrofitting with only energy reduction as a goal can have a negative impact building occupants. For example, occupants may become dissatisfied with thermal conditions or indoor air quality due to the introduction of aggressive thermostat setbacks or reduced ventilation rates. Or occupants may lose the opportunity to control their indoor environment with the introduction of automatic sensors or windows that don't open. Naturally, occupants will take matters into their own hands by covering up sensors, propping windows and doors open or adding space heaters or portal air conditioners, all of which can erode the energy savings retrofits were designed to achieve.

THE APPROACH

Professor Touchie and her team at the Building Energy and Indoor Environment Lab are working on building retrofit solutions that achieve environmental goals while providing occupants with comfortable spaces to live and work. Together they pair lab, field and modelling techniques to characterize existing building performance and investigate new building retrofit options with occupant engagement strategies such as surveys, interviews and photo-based data collection to understand the impacts of retrofits on people. When combined, this approach provides a more holistic view of building retrofits. Much of Professor Touchie's research is focused on how to improve building performance in the social housing sector which is particularly challenging given the tight budgets and particular vulnerabilities of the populations housed in these buildings. One example of a current project is assessing the performance of Canada's first EnerPHit retrofit of a high-rise social housing building. Here, her team is instrumenting resident suites with indoor environmental quality sensors, submetering energy use and interviewing the residents about their perceptions of the building and elements that contribute to or detract from their wellbeing.



THE IMPACT

Professor Touchie is working with industrial partners like the Toronto Community Housing Corporation to pilot new solutions in their buildings which are designed to reduce energy consumption while improving the lives of residents.

WHAT'S NEXT?

The team is exploring the use of wearable technology like smart watches to capture real-time occupant feedback and use this to make changes to building operation.

BUILDING ENGINEERING RESEARCH

SYNTHETIC IMAGES -DRIVEN VISUAL MODEL TRAINING FOR CONSTRUCTION APPLICATIONS

Prof. Daeho Kim

THE PROBLEM

As for the artificial intelligence development of robotic solutions, heavy reliance on deep neural network (DNN)-powered vision models at this time is unprecedented. However, the progress on DNN model development in the AEC industry lags far behind that of other industries. The reason behind the gap is not solely because of the gap in knowledge or science but the lack of shared training datasets. Absent such data, many construction studies are bound to result in overfitted models with low accuracy and scalability, not even benefitting from the merits of deep architectures. What is even worse is that the absence of a shared dataset makes competitive benchmark among researchers infeasible and thus hinders knowledge discovery: since the used datasets—not to mention they are small and biased—are different by studies, fair comparison, and competition are not allowed and thus, the discovery of new knowledge for construction DNN model development is extremely lagged.

THE APPROACH

Against this backdrop, Prof. Kim develops a computational framework that can synthesize and label real-like construction images simultaneously in a fully automated way and validate the effectiveness of the synthetic images on construction DNNs' training, discovering unknown pieces of knowledge required for non-real data-driven DNN training. Please see the below example images generated from our framework automatically.

THE IMPACT

Granted the number of synthesizable images is limitless, and all the labels of interest can be given without any manual inputs, it is worthwhile to investigate the potential of synthetic images. Once its effectiveness is confirmed, the non-real data-driven training will be highly likely to impact the conventional approach of DNN model training in construction academia.

WHAT'S NEXT?

Through this research, the following research questions are to be answered:

· Are synthetic images effective in DNNs' training from any perspective?

· Can synthetic data-based training result in the same effect as real data-based training?

· How many synthetic images will be required to outperform real data? How many synthetic images will be required to outperform real data?

· How would the image variations result in the different performance of construction DNNs?

· Given enough training data, how can we tune existing DNN architectures, cost functions, and learning algorithms to achieve the best construction DNN model?

Once the effectiveness of the synthetic data is confirmed, the research team will have the dataset open to the public—the Canadian Society for Civil Engineering (CSCE)—so that Canadian researchers can benchmark our dataset and models to develop and further enhance their own DNN models.

BUILDING ENGINEERING RESEARCH

INDOOR MICROBIOLOGY AND ENVIRONMENTAL EXPOSURE

Prof. Sarah Haines

THE PROBLEM

We spend the vast majority of our time indoors where we are exposed to a variety of abiotic and biotic contaminants. Indoor inhalant allergens are responsible for around 44% of diagnosed asthma cases. Asthma impacts approximately 3.8 million Canadians, disproportionately impacting lower income communities who are at higher risk for mold and moisture exposure due to inadequate housing. Increased temperatures, wet weather events and flooding due to the impacts of climate change may influence mold growth and subsequently human microbial exposure. The built environment must be further explored to determine influences of moisture and interactions between microbes, chemicals, and viruses. We need to better understand and predict mold growth indoors to limit impacts on human health and create healthy and sustainable indoor environments.

THE APPROACH

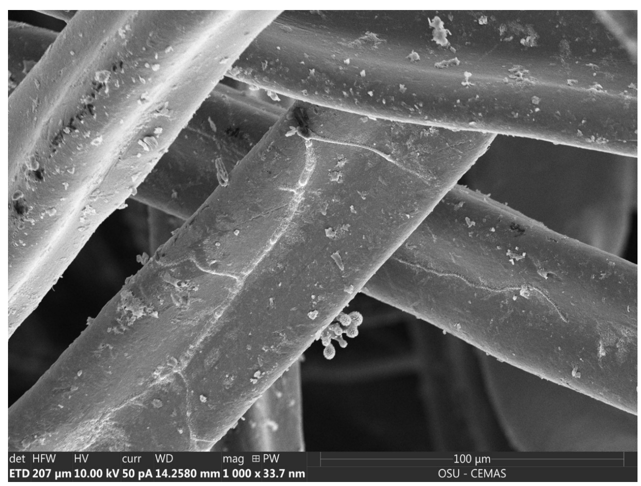
Professor Haines' goal is to utilize cutting-edge microbiology techniques such as next-generation sequencing, metatranscriptomics and bioinformatics to strengthen indoor environmental quality. By modeling microbial growth on common indoor surfaces, she can better predict and identify mold growth indoors. Utilizing dust from indoor environments Professor Haines can analyze the indoor microbiome as well as the presence of chemicals and viruses in these spaces. Her work focuses on microbial growth on common indoor materials as well as the volatile organic compounds and microbial volatile organic compounds they produce.

THE IMPACT

Findings from her research will influence recommendations for indoor spaces with broad implications for managing microbial growth, chemical emissions, and exposures. This will aid in the development of healthy sustainable indoor spaces and buildings, particularly for low-income communities who may be more susceptible to impacts of increased indoor moisture.

WHAT'S NEXT?

Predictors and indicators of microbial growth better than visual or olfactory inspection are necessary to enhance mold detection. Future work will aid in developing efficient quantitative methods for mold detection in built environments.



A scanning electron microscopy image of microbial growth on carpet fibers

BUILDING ENGINEERING RESEARCH

AI SOLUTIONS FOR BUILDING ENERGY SYSTEMS

Prof. Seungjae Lee

THE PROBLEM

A building is a complex system that comprises various components and subsystems. Therefore, optimizing the design and operation of this complex system to improve building energy efficiency and indoor environmental quality requires extensive engineering effort. The problem is that individual buildings differ from each other; this fact makes the optimization practically even more challenging in the real world. Each building has its own physical characteristics because of its unique shape, layout, enclosure, and subsystems. In addition, individual buildings are exposed to diverse weather conditions while consuming different types of energy. Moreover, building occupants have different preferences, needs, and behavioural patterns, which significantly affect building behaviour. The uncertainty in weather, occupants' behaviours, and energy supply is another obstacle for human engineers in optimizing buildings.

THE APPROACH

Professor Lee conducts research to develop artificial intelligence solutions that optimize building energy systems to improve building energy efficiency and indoor environmental quality. His research pursues seamless integration of building science domain knowledge and data to develop feasible, effective, reliable, and human-understandable solutions. Modern probabilistic machine learning, causal inference, and stochastic optimal control technologies are core tools in his research.

His current project aims to develop a knowledge-informed machine learning approach for optimal control of building heating, ventilation, and air conditioning (HVAC) systems. The proposed approach will allow developing an optimal HVAC controller for each building without extensive effort, which can (i) make reliable decisions with building science domain knowledge in cases where data are insufficient and (ii) efficiently collect necessary data actively to be continuously self-tuned, in a manner similar to that of experienced engineers. The project focuses on office buildings, which account for more than 40% of the energy used by the commercial building sector. To this end, existing simulation tools and empirical/forward models, building energy databases, state-of-the-art Bayesian surrogate modeling and reinforcement learning techniques are used.

THE IMPACT

Adoption of advanced building control technologies, in conjunction with advanced sensors and actuators, is expected to save more than 30% of building energy consumption, while 20% of commercial buildings peak load can be temporarily managed or curtailed to provide reliable grid services. Professor Lee's research will accelerate the pace of the adoption in the real world by significantly reduce the engineering effort required to implement advanced optimal control technologies in buildings.

WHAT'S NEXT?

Professor Lee envisions a future in which human engineers and artificial intelligence closely cooperate to improve building energy performance and indoor environmental quality not only in building operation phase but also in design phase. Towards this vision, he will continue to work on the development of scalable artificial intelligence solutions for building energy systems.

BUILDING ENGINEERING RESEARCH

CORROSION: THE CANCER OF METALS AND ASSOCIATED STRUCTURES

Prof. Ibrahim Ogunsanya

THE PROBLEM

Many critical infrastructures are under constant degradation from their aggressive environmental conditions. Most degradations are due to the corrosion of metals used in various infrastructures. For example, corrosion is the main deterioration mode of steel reinforced concrete structures and significantly reduces their functionality, reliability, service life, and safety. Corrosion, in its cancerous nature, has created a multi-billion-dollar infrastructure deficit across several engineering sectors, including the civil/structural, mechanical/automotive, and chemical/nuclear areas that Prof. Ogunsanya research in. Given the indisputable societal and economical importance of the impact of corrosion, it is essential to develop strategies on corrosion control and management practices throughout the nations' infrastructure.

THE APPROACH

Professor Ogunsanya's research utilizes cutting-edge methodologies, electrochemical and corrosion techniques, nanoscale characterization and microscopy techniques, as well as thermodynamic, numerical, and machine learning modelling to: (i) understand the corrosion characteristics of existing metals and alloys (ii) develop novel corrosion-resistant alloy and strategies that are fit for specific corrosion-affected regions, and (iii) understand the efficacy of these newly developed alloys and strategies on improving the service life and life-cycle costing of our infrastructure.

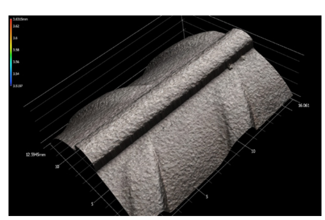
THE IMPACT

One of Prof. Ogunsanya's research area is in ensuring corrosion durability of reinforced concrete structures. The image below, showing corrosion-affected areas on the Gardiner Express Way in Toronto, is reflective of the current state of our aging infrastructures.
On this research topic, Prof. Ogunsanya have on-going collaborations with the Ontario Ministry of Transportation to find the most sustainable and durable concreting materials needed to build resilient transportation infrastructures across Ontario.

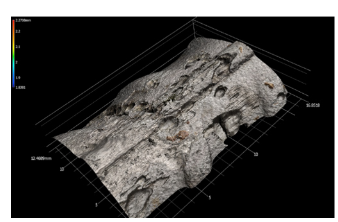
WHAT'S NEXT?

Collaborations with private and public sectors on corrosion-related topics are on-going and are being sought. Continued study on corrosion of metals is critical to ensuring infrastructure durability and training highly qualified personnels that will provide appropriate knowledge and quantitative strategies needed to combat current and future corrosion problems.

Corrosion-affected areas on the Gardiner Express Way in Toronto



Before corrosion



After corrosion

MINING/GEOTECHNICAL ENGINEERING RESEARCH

DOING MORE WITH THE DATA WE HAVE: UNDERSTANDING STRESS IN DEEP MINES

Prof. Sebastian Goodfellow, Prof. John Harrison

THE PROBLEM

Knowledge of local stress conditions is of critical importance for mine design and mine management. However, stress is a challenging quantity to measure because it can be highly variable across a region of interest and the available methods can be time-consuming, expensive, and have high rates of failure. As a result, measurements are sparse and mines may therefore be designed and operated with an uncertain understanding of the stress state.

THE OPPORTUNITY

Over the past decade new technologies such as Acoustic Televiewer (ATV) for geotechnical and geological logging of boreholes, the Cloud, and Machine Learning (ML) for data analysis have emerged, and the adoption of these has now reached a tipping point in the mining industry. We have observed an 8-fold increase in ATV data collection by the Canadian mining industry since 2014, an increase that has largely been driven by improvements in the technology. As a result, the mining industry is now sitting on big ATV datasets that were gathered for borehole logging, but have potential value that far exceeds this. The opportunity we are exploring is to apply ML techniques to ATV data in order to obtain novel and improved assessments of the local stress state.

THE APPROACH

The largest barrier to widespread adoptions of ATV technology is the labour-intensive nature of ATV data processing, which involves the manual identification of breakouts, fractures, and faults. We are developing a suite of computer vision ML models that automate the processing ATV data, and coupling these with a novel Bayesian framework for in situ stress we have recently developed. This combination of large data sets and a Bayesian framework will allow for probabilistic uncertainty quantification, which is vital for the effective application of stress data to mine design and ground control decisions.

THE IMPACT

As shallow deposits become exhausted, mining targets are extending to greater depth, and are now approaching 2 – 3 km in Sudbury, Ontario for example. In these conditions, engineering design decisions made without an accurate and complete understanding of stress conditions exposes underground workers to risk of death and serious injury following structural failure, and may threaten the overall financial feasibility of a mine. By developing a methodology and tools for robust real-time in situ stress estimation, we will be able to provide decision making intelligence to mine managers allowing them to make more informed decisions.

WHAT'S NEXT?

Collaborations with mining companies are being pursued to provide datasets and test sites for the proposed technology. We plan to test it at multiple sites to identify issues and to evaluate its efficacy. To translate the technology effectively and truly innovate, these technologies will be observed and refined through multiple iterations of the Build -> Measure -> Learn product development cycle.

MINING/GEOTECHNICAL ENGINEERING RESEARCH

TACKLING ROCK MECHANICS UNCERTAINTY FOR ROCK ENGINEER DESIGN

Prof. John Harrison

THE PROBLEM

Rock engineering takes place in particularly complex materials: rock masses that comprise blocks of intact rock of various sizes and shapes bounded by fracture surfaces of irregular geometry. The mechanical properties of rock masses are therefore difficult to characterize, spatially variable and hence somewhat unpredictable. Although physical testing of samples of a rock mass forms a routine part of the rock engineering design process, it is not feasible to test the quantities or size of samples necessary to obtain robust estimates of design values. As a result, the design values used in rock engineering are uncertain and the safety of the subsequent rock engineering designs unknown.

Modern geotechnical engineering is evolving to use limit states design, which requires variability to be accurately determined and uncertainty to be quantified. So how should we quantify unpredictability in rock masses, such that spatial variability, uncertainty and the currently inevitable vagueness are robustly accounted for in a fashion that both supports these modern design techniques and allows the safety of rock engineering designs to be determined?

THE APPROACH

Professor Harrison and his research group are undertaking fundamental research on the development of probabilistic and non-probabilistic methods for rock engineering design.

A number of techniques are being applied to the problem. The group has recently developed a novel multivariate model for in situ stress, and this allows variability of stress to be quantified. The group is also developing hierarchical Bayesian data analysis techniques that allow robust determination of engineering design values from rock mechanics data. Finally, the problem of spatial variability is being investigated through development of cluster analysis for multiple metric spaces.

THE IMPACT

This work is being done in the context of reliability-based design codes, as Professor Harrison is also working on the international development of these for geotechnical engineering. Professor Harrison expects that within five years international design codes for geotechnical engineering will be developed sufficiently to permit robust incorporation of the key aspects of rock mechanics unpredictability. Within ten years he expects to see the results of this research applied widely in rock engineering design and construction.

WHAT'S NEXT?

The introduction and refinement of codes based on reliability based design will influence rock engineering and rock mechanics practices on a global level, reducing the level of risk and improving the economic efficiency of construction and mining sites. Professor Harrison's research is directly supporting this, and will evolve to tackle further problems in this area.

MINING/GEOTECHNICAL ENGINEERING RESEARCH

ROCK FRAGMENTATION AND BLASTING RESEARCH

Prof. Bibhu Mohanty

THE PROBLEM

Improved productivity and safety in mining and excavation projects are key objectives in all such operations. These are essential elements for extending mine life while minimizing hazards to the surrounding areas associated with such operations. Because of its multi-disciplinary nature in melding key elements from shock waves and detonation physics, explosives chemistry, material science, rock mechanics, and geology, it represents a formidable challenge. Essentially, the problem can be viewed as a comminution process, be it drilling, blasting, crushing or grinding; the only difference among these being the time duration of the applied load, e.g. from milliseconds as in drilling to micro-seconds as in blasting to time scale in seconds as in crushing and grinding of fragmented rockmass. It thus presents a formidable challenge even for a homogenous target rock in terms of predictability.

THE APPROACH

The key facets of the task are: a) characterization of target rock mass in terms of strength and its load-rate sensitivity spanning over two orders of magnitude, b) explosive energy partitioning between shock and gas expansion phase; precision of initiation sequence in use in boreholes, c) accurate assessment of fragmented rock mass, d) cost breakdown of downstream processes such as loading, crushing and grinding, and e) proper assessment and abatement of environmental hazards such as blasting vibrations, fumes, and effect on surrounding structures.

THE IMPACT

The main objectives are to improve productivity through appropriate matching of the strength and related geological properties of the target rockmass against applied load (e.g. in drilling, blasting, and crushing) and thereby improve predictability, safety, and increased mine life.

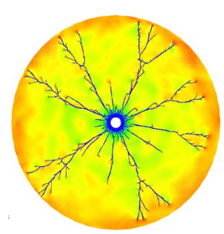
WHAT'S NEXT?

The subject presents formidable challenges requiring a truly multi-disciplinary /approach. It involves development of novel laboratory-based experiments to characterize dynamic strength properties of rocks, explosive-rock interactions in small-scale blasting experiments to assessment of full-scale blasts in operating mines. This is to be complemented by application of advanced numerical codes, with results from laboratory experiments to develop truly predictive models.

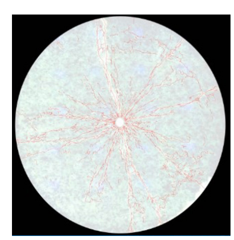
A good example of this long-term challenge can be seen in the figures below. The excellent tunnel excavation results in a granitic rock were obtained through careful matching of the characteristics of the in-situ rock and the explosive and initiation system, albeit largely on an empirical and trial-and-error basis. The accompanying figure shows a comparison between numerical model prediction of resulting crack pattern for only the initial stress-wave action against actual mapping of the shock wave induced fracture pattern in a cylindrical sample of granite in the laboratory. As apparent, the agreement between prediction through numerical modeling and the actual experiment can be considered only qualitative at present. Research is continuing on developing a more advanced model that will duplicate experimental results for a range of borehole and blasting conditions.

Controlled blast designs produced high quality tunnel walls with minimum bootlet. Blast broke 8.54 m (ave. length of blastholes). There were no bootlegs in the centre of the round (e.g. 100% pull). Blast rounds length to runner diameter ratio is >2.0

Length of round: 8.54 m Tunnel Dimensions: 3.5m (w) x 3.3 m (h)



Simulation



Experiment

MINING/GEOTECHNICAL ENGINEERING RESEARCH

CEMENTED PASTE BACKFILL

Prof. Murray Grabinsky

THE PROBLEM

Mines produce a significant amount of waste material in the form of finely crushed rock and water, called tailings. The management of these tailings poses a significant engineering challenge. Conventional forms of tailings disposal have not performed well resulting in significant adverse impacts on the environment, surrounding communities, and the operation of the mine. How can we better manage mine tailings?

THE APPROACH

Professor Grabinsky's research group focuses on liquefaction of strong ground, in particular the liquefactionof mine tailings mixed with a binder and called Cemented Paste Backfill (CPB). The research goes beyond the traditional areas of liquefaction research and explores exciting new areas including the effects of binder hydration, of sustained high frequency loading, heterogeneous in situ conditions and the use of rheology.

Field sites are an important part of the research program and Professor Grabinsky and his students have worked at mines located in Canada, South America, Africa, Europe and Asia. Field work is complemented by the development and application of numerical models and laboratory testing with the unique facilities, developed in-house, for CPB research.

WHAT'S NEXT?

Research will continue to go beyond traditional areas of liquefaction research and include the effects of binder hydration, unsaturated water phases and frequency dependence under sustained high frequency loading.

THE IMPACT

The research is being done in partnership with mining companies that produce large quantities of tailings. Professor Grabinsky's research is leading to new methods for converting these tailings to CPB and for efficiently and safely handling the CPB.

MINING/GEOTECHNICAL ENGINEERING RESEARCH

MINING UNDER EXTREME DEEP AND HIGH STRESS CONDITIONS

Prof. John Hadjigeorgiou

THE PROBLEM

As the mining industry matures in many regions of the world, its future becomes increasingly dependent on the ability to exploit deep mineral resources safely and efficiently. Mines around the world continue to excavate at greater depths, in more challenging ground conditions, facing logistical and environmental challenges rarely seen in shallow mines. A high level of understanding and technically sound approaches are essential to deal with the significant geotechnical (from squeezing ground to rockbursts) and logistical (transportation, ventilation) issues of deep and high stress mining, requiring best practice and innovation to be implemented. Arguably, the greatest challenge associated with deep mining is the management of geomechanical risks associated with high stress environments as these can cause rapid degradation of mine infrastructure and pose a threat to the safety of mine workers. Such an environment calls for intensive and innovative ground control systems.

THE IMPACT

The results of our research have been implemented at mine sites worldwide and contribute significantly to the safety of mine workers. Additionally, they have important monetary implications in mitigating rehabilitation and production costs amounting to hundreds of millions of dollars. In a broader context they significantly improve the feasibility of mining deeper deposits, which is a key strategic issue for Canada as well as for mining companies operating world-wide.

WHAT'S NEXT?

Our research program offers an important contribution to developing an overarching strategy of understanding, mitigating and managing technical risk associated with mining under extreme deep and high stress conditions.

THE APPROACH

Our research program addresses fundamental and applied research needs in managing extreme ground conditions of mining induced seismicity and squeezing ground conditions. Working with our Canadian and international industrial partners, we employ a multifaceted approach using extensive field studies, sophisticated state-of-the-art numerical tools, and some of the most innovative impact testing programs. This allows us to develop practical solutions capable of mitigating the geomechanical risk associated with mining under extreme ground conditions.

MINING/GEOTECHNICAL ENGINEERING RESEARCH

MINING, WATER AND THE ENVIRONMENT

Prof. Lesley Warren

THE PROBLEM

As the demands for finite water resources begin to outpace supply, there is an imperative need for innovative solutions to address its consumption and contamination by sectors posing the most risk to water security. Mining is currently the second largest industrial user of water after power generation, and current technologies cannot meet the growing imperative to reduce the amount of water used by mining activities and eliminate possible wastewater-associated environmental risks. While green technologies are viewed as the cornerstone to national and international, sustainable development plans, they require even greater mineral extraction which will exacerbate the current global water crisis without innovative solutions. There is currently insufficient knowledge of how microbes, occurring in mining waste contexts, affect wastewater quality and waste stability. Such knowledge is required to enable proactive, adaptive management that can better steward the environment by mine operations globally.

THE APPROACH

Within Prof. Warren's research group, an array of genomics technologies integrated with high resolution geochemistry are used to identify the key processes and controls (including microbial), that determine water quality in mining contexts.

She is the principal investigator on The Mining Wastewater Solutions (MWS) Project, which is revealing new understanding of how microbes affect sulfur cycling in tailings impoundments to better prevent potential impacts from these sulfur compounds in receiving environments. Her industry partners include Glencore INO, HudBay Minerals and Rambler Metals and Mining.

She is also the principal investigator on The Base Mine Lake (BML) Biogeochemical Development Project, which is determining the water quality development in this first pit lake in the Alberta Oil Sands and identifying the key processes and microbial controls impacting oxygen concentrations; a key metric for success of this water capped reclamation tailings technology with industry partner Syncrude.

THE IMPACT

By revealing these previously hidden microbial engineers and delineating the key processes and controls, the results of Prof. Warren's research open the door to smarter management practices and reduced risks of environmental impacts and liabilities associated with water use for the mining sector. Ultimately this will help ensure the sustainability of the Canadian resource sector and secure Canada's freshwater supplies.

WHAT'S NEXT?

Next steps involve the development and beta testing of predictive models, monitoring assays and possible biological treatment strategies that will translate these knowledge discoveries into practical tools enabling proactive, adaptive management sulfur compounds; as well as expanded characterization of pit lake biogeochemical cycling that will support smart pit lake design as part of reclamation and closure for the Alberta oil sands region.

MINING/GEOTECHNICAL ENGINEERING RESEARCH

MINE MODELLING AND ANALYTICS LAB

Prof. Kamran Esmaeili

THE PROBLEM

The easily accessible ore deposits are being depleted rapidly and new ore reserves are lower in grade, more complex geologically and more challenging technically to discover and extract. Discontinuous and intermittent mining process monitoring approaches as well as decision making based on partial information and missing facts that are usually employed in mineral resource management, are no longer suitable to address these challenging and complex issues. How can we integrate sensor-based data and advanced data analytics and numerical modeling techniques to make intelligent decisions in mining?

THE APPROACH

Professor Esmaeili is developing practical solutions for mining industry to increase efficiency and safety of mine operations. He has developed integrated remote sensing and data analytics techniques for better characterization of intact rock and rock mass properties, blasted muckpiles, mapping pit walls and heap leach pads.

The effective extraction and utilization of an ore body requires sound knowledge of the mineral resource and accurate information on the extraction process. Knowledge of the resource and the extraction process in mining operations can be limited due to gaps in collected data, subjective and inconsistent characterization, and limited data sharing. Professor Esmaeili and his research team have investigated the development of remote sensing-machine learning solutions for real time mining data collection and decision making. The research has focused on using high quality sensing data together with image analysis techniques to develop intelligent monitoring systems for: optimizing drilling and blasting process; investigating mine design compliance; and mine infrastructure and earth works monitoring.

THE IMPACT

Professor Esmaeili is working with several mining companies. Research completed in the Mine Modeling and Analytics lab has had significant impact on efficient mine design and continuous process control and optimization. The implementation of the developed intelligent solutions has led to more cost-effective mining operation and improved utilization, throughput, and safety of mining/milling process.

WHAT’S NEXT?

Professor Esmaeili’s research group is working on a variety of advanced remote sensing-machine learning methods including hyperspectral sensor to improve mining and extraction process.

MINING/GEOTECHNICAL ENGINEERING RESEARCH

GEOMECHANICS FOR ENERGY TRANSITION

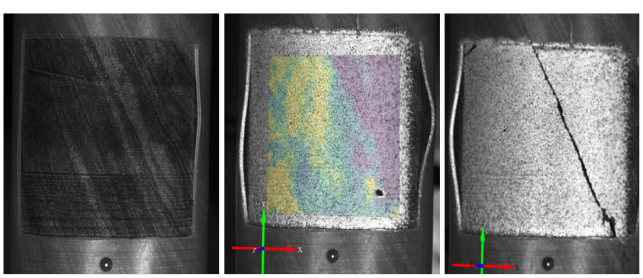
Prof. Giovanni Grasselli

THE PROBLEM

Any rock mass contains discontinuities at multiple sizes, orientations, and spatial distributions. Such discontinuities greatly influence the hydro-mechanical response of the rock mass to any engineering activities, resulting in an anisotropic response of the rock formation. The variation of the mechanical properties of the rock with respect to the orientation of the discontinuity is a dominant factor in controlling fracturing processes and failure, potentially complicating engineering studies in rock masses, particularly in tunneling, excavation, reservoir exploration, and hydraulic fracturing. Thus, significant effort is needed to gain further understanding of rock anisotropic behavior and enhance its characterization.

THE APPROACH

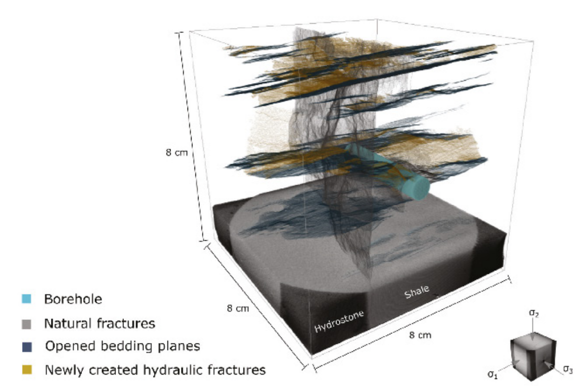
The GeoGroup and the Transparent Lab at the University of Toronto, led by Prof. Grasselli, continues to endeavour in unravelling rock anisotropy and its impacts on engineering studies. Research in this area is supported by the use of a unique combination of equipment including a 3D digital image correlation system (DIC), 3D printers, 3D surface scanner, precision CNC milling machine, micro- and nano-indenter, X-Ray micro-CT, and a true triaxial testing system. This array of equipment allows for in-depth experimental investigation of the evolution of the fracturing process in rock from both a microscopic and macroscopic scale. Additionally, the value of the laboratory data can be complemented and enhanced through numerical modelling The research group focuses on the finite-discrete element method (FDEM), which can simulate complex multi-physics fracturing problems and provide insights to the rock behaviour under complex conditions that are hard to achieve experimentally.



Failure and strain field observations using DIC

THE IMPACT

Research within the group has thus far uncovered the impacts of rock anisotropy and their influences on fracture propagation. These findings are being extended to understand complex rock response and inform several engineering sectors that include optimizing oil and gas recovery, geothermal energy, energy storage, reducing risks of wellbore, slope and tunnel instability and ultimately ensuring the safety of individuals and stability of structures.



In-depth characterisation of the fractures post-test

WHAT'S NEXT?

Next steps involve laboratory testing to understand the evolution of fracturing under extreme thermal and pressure conditions to extend the research into larger geo-energy applications. This also involves, scaling up closer to field scale through a "Megablock experiment" that will help translate these discoveries and learnings into practical tools.

Affiliated Centres and Institutes

Centre for Resilience of Critical Infrastructure
Institute for Sustainable Energy
Lassonde Institute of Mining

Primary Research Facilities

Advanced Simulation and Structural Dynamics Laboratory
Centre for Building Excellence Laboratory
Drinking Water Research Laboratory
Hub for Advancing Buildings
Information Systems in Infrastructure & Construction Lab
Intelligent Transportation Systems Centre & Testbed
Groundwater Research Laboratory
Rock Fracture Dynamics Facility
Structural Testing Facilities

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