UNIVERSITY TRANSPORTATION CENTER
FOR UNDERGROUND TRANSPORTATION INFRASTRUCTURE

Semi Annual Progress Report #2
Submitted to

United States Department of Transportation (USDOT), Office of the Assistant Secretary for Research and Technology (OST-R)

Federal Grant number: 69A3551747118

Project Title: US DOT Tier 1 University Transportation Center for Underground Transportation Infrastructure (UTC-UTI)

Marte Gutierrez, PhD
J. R. Paden Distinguished Professor and Director of UTC-UTI
Colorado School of Mines
Coolbaugh 308, 1012 14th St., Golden, CO 80401
Tel: (303) 273-3507, E-mail: mgutierr@mines.edu

October 30, 2019

DUNS#: 01-0628170
EIN#: 84-6000551

Recipient Organization: Colorado School of Mines, 1500 Illinois St., Golden, CO 80401

Project/Grant Period: November 2016 – September 2022

Reporting Period: April 1, 2019 – October 30, 2019

Report Frequency: Semi-annual

Signature:

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

CAL STATE LA

LEHIGH UNIVERSITY

University Transportation Center for Underground Transportation Infrastructure (UTC-UTI)

UTC-UTI is a Tier 1 University Transportation Center funded by the U.S. Department of Transportation under the FAST (Fixing America's Surface Transportation) Act. UTC-UTI is devoted to the advancement of Underground Transportation Infrastructure as cost-effective, safe and sustainable solution to increasing demand for conveying people, goods and services particularly in many urban areas in the US. UTC-UTI addresses the FAST Act Research Priority Area: "Improving the Durability and Extending the Life of Transportation Infrastructure." UTC-UTI is a collaborative effort between Colorado School of Mines (CSM), California State University Los Angeles (CSULA) and Lehigh University.

1. ACCOMPLISHMENTS

1.1 Major Goals of the UTC-UTI

The main objectives of UTC-UTI are to:

1. Develop technologies that will improve the durability and extend the life of new and existing UTIs;
2. Educate and train the next generation of UTI engineers and personnel; and
3. Transfer research results and technology to industry.

The main research focus of the University Transportation Center for Underground Transportation Infrastructure (UTC-UTI) is the development and deployment of major improvements in the design, planning, construction, maintenance, operation, retrofit and expansion of underground transportation infrastructure to make them more durable and to extend their lifetime. These developments will be realized by moving away from largely empirical and tradition-based procedures to an intelligent and data-driven system that uses recent progress in condition monitoring, sensing and asset/performance assessment, as well as in new construction materials and technologies. The research will emphasize on the following specific research topics: 1) Application of new materials and technologies; 2) Condition monitoring, remote sensing and use of GPS; and 3) Asset and performance management.

1.2 Progress and Accomplishments

1.2.1 Research Activities

During the reporting period, UTC-UTI funded a total of 14 research projects (8 at CSM, 4 at CSULA and 2 at Lehigh). Highlights of these projects are given below.

<u>Research at Colorado School of Mines</u>

TITLE OF THE PROJECT: Data driven risk mitigation of cross passage and cavern deformation

<u>SUMMARY</u>: This research is using both experimental field monitoring data and adaptive computational modeling to better understand ground-structure interaction and to continuously update estimates of in-situ conditions (both in the ground and structure) for real time risk management and construction decisions. The project is utilizing rich data sets from the Seattle Sound Transit Northlink tunnel project and the LA Metro Regional Connector tunnel project, as well as initiating efforts to use data from the Northeast Boundary tunnel (NEBT) project in Washington, DC. This data collection was not funded by the USDOT grant; however, we have been granted access to use the data. The objectives of the project are to: (1) characterize actual and designed-for liner loads when installed via pressure balance TBMs; (2) characterize impact of cross-passage construction on segmental lining; and (3) use a combination of field measurements collected during sequential excavation method construction plus computational modeling to better characterize ground/structure interaction and ground properties.

<u>PROJECT STATUS</u>: (Obj. 1) Seattle Northlink complete (see prior report). Our participation in the NEBT project liner load instrumentation has begun successfully. We will continue this work with the NEBT

project team. (Obj. 2) The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is complete and 3D finite element modeling is in progress. (Obj. 3) The interpretation and analysis of field measurements for LA metro cavern excavation are complete, and sensitivity and reliability analysis for computational modeling inputs are ongoing.
MILESTONES ACCOMPLISHMENTS AND DATES: As of September 31, 2019: For objective 1, two conference paper have been written and published, and two journal papers are under development. For objective 2, one conference paper has been written and published, and one journal paper is under development. For objective 3, one conference paper has been written and submitted and one journal paper is under development.
PLANNED ACTIVITIES: NEBT tunnel analysis will ramp up and LA Metro study will be completed in the next year. We aim to develop a traceable and objective procedure to identify reliable ground properties based on field measurements from cavern sequential construction.
PROJECT PERSONNEL: Dr. Mike Mooney, Dr. Marte Gutierrez, PhD students Tamir Epel and Haotian Zheng.

TITLE OF THE PROJECT: Functional reliability of tunnels and its impact on transportation network resilience
SUMMARY: Tunnels are typically one of the most critical links in a transportation network and they greatly undermine network resilience when they lose functionality (either entirely or partially) due to hazardous loading conditions. Closure or limited access of traffic tunnels (function loss) is very costly and has great negative impacts on the public. Each tunnel owner or manager typically analyzed these events in a case-by-case basis. There is currently a lack of systematic data collected or analysis done to investigate the overall trend for the occurrence and severity of such events. A systematic analysis of tunnel function-loss cases can answer some of the most critical questions of interest to tunnel owners. This project aims at developing two fundamental elements to enable this analysis, namely 1) a tunnel operation data collection framework that can be adopted for critical tunnels across the country, and 2) a probabilistic framework for quantifying tunnel resilience (functionality loss) as conditional distribution of hazard type and intensity. The project team will work closely with local DOT to implement some of the developed models and tools with the vision to expand the application of the research outcome nationwide.
PROJECT STATUS: The PI met with CDOT Data & Database Architect (Weiyan Chen) and obtained access to the CDOT traffic management system (CTMS) database. The graduate student has been extracting functionality loss data for major tunnels on I70. The team has also begun to develop probabilistic simulation tool for tunnel functionality loss prediction. So far, the modules for fire and hazardous truck queuing events have been completed. But the team is still working on organizing the data from CTMS so the simulation tool can be validated.
MILESTONES ACCOMPLISHMENTS AND DATES: No significant milestone was reached during the reporting period.
PLANNED ACTIVITIES: The research team will focus on two main tasks in the next reporting period. The first one is to complete extracting and organizing tunnel operation data from CTMS system. Then the team will use the obtained data to guide the development and validation of the probabilistic simulation tools for tunnel resilience prediction.
PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Shiling Pei and Sandeep S Khetwal (Graduate Student).

TITLE OF THE PROJECT: Probabilistic rock mass quality prediction model and its application to tunneling design
SUMMARY: Tunneling in fractured rocks must address uncertainties in a rock mass quality measure due to the inherently heterogeneous nature of the rock mass. Traditional deterministic methods for the assessment of rock mass quality are not based upon a complete understanding of these inherent uncertainties, which can result in adverse impact on overall tunnel performance. To address this problem, a Monte Carlo simulation (MCS)-based uncertainty analysis framework is proposed to probabilistically

quantify the uncertainties in the Q-system of rock mass classification for tunneling. The main objectives of this project are: 1) Establish a probabilistic Q prediction model based on the Q-log results from the general and location-specific exploration based on a probability distribution function (PDF) of Q-value along the tunnel alignment and the corresponding PDF of support design based on Q-based support chart. 2) Compare prediction results of Q-value using the proposed method and other previous approaches with the actual Q-value on site for validation purpose and conduct sensitivity analysis to evaluate the robustness of the proposed model. 3) Validate the relationship between site-specific monitored deformation data and actual Q/Span and compare it with Q/Span-deformation relationship. The proposed framework is envisioned to be capable of systematically assessing the uncertainty in the rock mass quality measure before construction as well as providing insightful information for the probabilistic evaluation of the ground response and support performance of underground structures.

PROJECT STATUS: This project has started in January 2017 and is now in the final stage of being completed. The probabilistic Q-based prediction model using MCS technique was applied to the Shimizu Highway Tunnel in Japan and the engineering feasibility study of the future extension of the Eisenhower-Johnson Memorial Tunnel (EJMT).

MILESTONES ACCOMPLISHMENTS AND DATES: The probabilistic Q-based prediction model using MCS technique is now complete. Reliability analysis on Shimizu Tunnel case study has been completed and application to EJMT is underway. One journal paper has been accepted and second one is under review.

PLANNED ACTIVITIES: We will complete the predicted probabilistic Q using a reliability-based method with deformation-based limit state function. The method will be applied to the case of the Shimizu Highway Tunnel in Japan.

PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Jamal Rostami and PhD student Hui Lu (Dr. Eunhye Kim, the previous PI for the project, left CSM and was replaced by Dr. Rostami).

TITLE OF THE PROJECT: Physical modeling to study tunnel squeezing under true-triaxial stress state

SUMMARY: Squeezing rock conditions have been causing major risks in the construction of tunnels in rock formations, especially at great depth and in weak and/or weathered rock masses. The tunnel excavation may induce a stress change with large deviatoric stress that can cause squeezing ground behavior. The mechanism of squeezing failure of tunnels is not clearly understood yet and the goal of this research project is to better understand the causes leading to squeezing ground phenomena. The objectives are to (a) identify the major causes of squeezing in soft rock; (b) quantifying the squeezing rates and amounts; and (c) develop experimentally verified squeezing criterion for broader application to tunnels. To achieve the research objectives, a series of novel true-triaxial compression experiments with simultaneous tunneling in rock are being conducted.

PROJECT STATUS: This project has started in August 2017 and has focused on developing the experimental setup for conducting the true-triaxial simulation experiments. The triaxial equipment along with the miniature tunnel boring machine (TBM) are now fully operational in the laboratory. Simulated rock materials made of a mixture of clay and cement have been prepared and characterized to document their physical, mechanical and viscous properties. A series of experiments has successfully been conducted on cubical rock specimens (one with a 'wished-in-place' lined tunnel and two TBM excavated tunnel) under the true-triaxial stress state to study the time-dependent convergence of the tunnel subjected to squeezing conditions.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Development of the experimental setup for true-triaxial testing of rock blocks; (2) selection of rock-like materials for batching and mixing to simulate the rock formation; (3) design and fabrication of a tunnel boring machine for excavating rock specimens while subjected to the true-triaxial state of stress; (4) successful simulation of tunnel excavation and squeezing conditions in laboratory environment.

PLANNED ACTIVITIES: Research plan for this year onward will be to perform experiments on the rock specimens using the fabricated tunnel boring machine.
PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Reza Hedayat and PhD student Ketan Arora

TITLE OF CURRENT PROJECT: Using InSAR time-series analysis to characterize tunnel-induced ground surface deformation

SUMMARY: In December of 2013, Big Bertha broke down approximately 300 m from where it started requiring major repairs for which a 37m deep shaft was constructed in the fall of 2014. Gaining access to the TBM required significant dewatering at multiple depths ranging from near surface to greater than 60m. Dewatering continued through February 2015, resulting in a 750m by 500m elliptical patch of subsidence with a maximum value of 3.5 cm measured near its center. We are using three separate Sentinel-1 InSAR datasets to verify the location of previously reported subsidence, as well as measure the quantity and spatial extent of post-subsidence rebound.
PROJECT STATUS: The current project started in January 2019. All three datasets have been downloaded and processed using a script written during Summer 2019 to automate processing of the InSAR Persistent Scatterers (PS). Currently the PS points are being examined and may be post-processed using a 4-D PS filter that we developed during the previous project (Wnuk et al., 2019).
MILESTONES ACCOMPLISHMENTS AND DATES: (1) Published results from first project in which we developed a 4D filter for InSAR PS that can be applied to tunneling induced subsidence (July 2019). (2) Acquired Sentinel-1 data covering downtown Seattle, spanning initial subsidence and subsequent rebound induced by dewatering during Big Bertha repairs (Summer 2019). (3) Wrote bash scripts to automate processing of InSAR PS pixels using GAMMA software (Summer 2019). (4) Acquired Sentinel-1 data covering downtown Los Angeles to begin processing for project #3 (September 2019).
PLANNED ACTIVITIES: (1) We plan to finish analysis of InSAR PS data for downtown Seattle (project #2) and submit to the Journal of Remote Sensing. (2) Use developed PS scripts to analyze Los Angeles Sentinel-1 data (project #3). (3) Acquire and process UAVSAR data spanning Los Angeles for comparison to Sentinel-1 data.
PROJECT PERSONNEL: Advisors: Dr. Wendy Zhou and Dr. Marte Gutierrez, and PhD Student Kendall Wnuk

TITLE OF THE PROJECT: Adaptive, predictive 3D geologic modeling for hard rock tunneling

SUMMARY: The expected geology along a proposed tunnel alignment is typically characterized based on an expert geologist's interpretations of some sparse initial investigations. As a predictive model of the true subsurface geology, a 3D geologic model has potential to aid in improving geologic understanding and to provide a baseline for subsequent design and analysis. The initial geologic model inherits uncertainty from input data and interpretations. As tunneling progresses in a hard rock setting, information on the encountered geologic conditions can be collected prior to installation of the final tunnel support. These new observations can be used to both validate existing geologic models and update model uncertainty to account for previously unseen structures. During excavation, this information can be used to adapt the geologic model to unfolding ground conditions and following excavation the calibrated geologic model can be used to inform potential expansions in the vicinity of the existing tunnel alignment. Model discrepancy is used to formulate and assess predictions of subsurface geology in the context of a 3D geologic model. Bayesian statistics provides a convenient framework for validating and updating predictions of subsurface geology considering new observations and information. The objectives of this project are: 1) To implement a data-driven 3D geologic modeling workflow that predicts geologic structures along a tunnel alignment with quantified uncertainty and 2) To utilize additional information gathered during excavation to adapt the geologic model to encountered geology in a Bayesian framework.
PROJECT STATUS: This project started in May 2017. Formulation and implementation of geologic model uncertainty assessment using an input-based, model discrepancy approach to investigate fault zones

intersecting tunnel alignments has been completed and is being used to draft a journal article as of Fall 2019.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) PhD thesis proposal was passed and defended in April 2019, with the student advancing to candidacy. (2) The proposed uncertainty assessment workflow has been successfully implemented and applied using a commercial 3D geologic modeling software (Leapfrog Works) with results on a simplified case study being submitted as a conference proceeding to WTC 2020.

PLANNED ACTIVITIES: (1) Processing of UAV acquired photogrammetric point cloud data to supplement 3D geologic modeling from historic datasets. (2) Formulation of geologic model validation and updating using Bayesian inference. (3) Combined modeling of geologic properties (e.g., rockmass classification) within a structural 3D geologic model.

PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez and PhD student Ashton Krajnovich.

TITLE OF THE PROJECT: Imaging ahead of tunnel boring machines with DC resistivity

SUMMARY: Tunnel boring machines (TBMs) are efficient tools for excavating the subsurface. However, there are dangers and risks during underground construction from unknown hazards ahead of tunneling operations, which may result in surface settlement and machine damage. Geophysical methods have the potential to improve underground construction projects by imaging the subsurface ahead of a TBM. Direct current (DC) resistivity is an attractive option because the electrical conductivities of soils, rocks, pipes, and other anomalous features vary over several orders of magnitude. The resistivity method is well understood in the context of surface and borehole geophysics, but it is seldom applied in underground construction and tunneling. Furthermore, the high conductivity of the TBM itself and the reduced number and available positions of electrodes that can be used on the cutterhead present challenges to the method during tunneling. In this study, DC resistivity data are collected with model TBMs in laboratory scale environments and compared with numerical simulations for better understanding the potential value to tunneling operations. Furthermore, we perform tests of various inversion algorithms to determine how reliable geophysical images can be produced in such a challenging environment. The resulting data shows that DC resistivity can detect hazards in front of a TBM.

PROJECT STATUS: This project started in September 2017 as an MS graduate research study. All laboratory experiments, numerical modelling and imaging studies have been completed as of Spring 2019 with results to be documented in an MS thesis.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Determination through laboratory measurements that electrodes from a DC resistivity system must be placed into probe-holes extending approximately 40%-50% of the diameter of the TBM, for minimal metal cutterhead influence (Oct-Dec 2017). (2) Detection of pipes, well casings and resistive voids in the laboratory setting using a DC resistivity system mounted on a model TBM (Jan-Apr 2018). (3) Numerical modelling using geophysical software designed for DC resistivity, demonstrating that experimental results agree with theoretical predictions (Aug-Oct 2018). (4) Numerical examination of various alternative DC resistivity configurations (Jan-Mar 2019). (5) Imaging studies to characterize the reliability of geophysical inversion of DC data in collected in front of a TBM (Nov 2018-Mar 2019).

PLANNED ACTIVITIES: This project was completed in May 2019 with the completion of MS degree of Max Mifkovic. A journal publication based on this thesis work is being completed.

PROJECT PERSONNEL: Dr. Andrei Swidinsky, Dr. Michael Mooney and graduate student Max Mifkovic.

TITLE OF THE PROJECT: The characterization of delamination processes with respect to waterjet shotcrete removal during tunnel liner repair and maintenance

SUMMARY: To circumvent the technical and operating challenges associated with the conventional removal and repair of shotcrete and concrete liners from underground workings, this research seeks to develop an innovative system that utilizes high pressure waterjet technology as the primary excavation tool. The underlying hypothesis is that waterjets are capable of selectively removing damaged areas of

support liners without structurally damaging the substrate or compromising the intact material adjacent to the area being excavated. The primary research objective is to quantitatively compare the damage caused by both conventional impact hammers and waterjet excavation methods during empiric cutting tests on instrumented panels using a shotcrete simulant overlaying wire mesh and a steel reinforced concrete substrate. The empiric results from laboratory testing strongly indicate that waterjet removal causes far less vibration within each sample as compared to mechanical impact hammers, as well as a significantly reduced collateral damage to adjacent material and the delamination between the shotcrete and the substrate.

PROJECT STATUS: All elements of the research have been successfully completed, where the final report is currently undergoing final revisions and should be completed by mid-November. A Ph.D. dissertation is also being prepared in parallel with this research which facilitated additional laboratory activities throughout 2019 to provide supplemental data. The student successfully defended his thesis proposal in September 2019.

MILESTONES ACCOMPLISHMENTS AND DATES: Within the most recent project reporting period, the following milestones were achieved: (1) Data analysis of the GPR scans of the test panels continued into September 2019 and will be incorporated into the student's thesis, (2) The final project report has been written and is undergoing revision. It is scheduled for completion by November 2019 and (3) Building upon this research, a Ph.D. Thesis dissertation is scheduled for completion in December 2020.

PLANNED ACTIVITIES:

After completion of the project, it is the intention of the project personnel to publish the results in several journals and conference proceedings. The two Ph.D. students who have worked on the project, Erik Charrier and Josef Bourgeois, have presented elements of the research to a variety of audiences both internal and external to CSM, including the 2019 SME Annual Meeting, the 2019 TRB Annual Meeting, and the upcoming 2019 CSM Tunneling Fundamentals Short-Course. Given the successful outcomes of this research, the data will be used to solicit additional support to advance the scope of this research, including field testing. Josef Bourgeois will also use the data to supplement his Ph.D. research project in pursuit of fulfilling his graduation requirements.

PROJECT PERSONNEL: Dr. Hugh Miller, Dr. John Steele, Mr. Brian Asbury, Ph.D. Graduate Students: Erik Charrier and Josef Bourgeois, Undergraduate Student: Devon Reasoner.

Research at California State University Los Angeles

TITLE OF THE PROJECT: The Applications of data science and big data analytics in underground transportation infrastructure

SUMMARY: This project applies data science, machine learning, and big data analytics to the construction, maintenance and performance of underground transportation infrastructure. The objectives are (1) developing advanced data mining and novel machine learning based methods for predicting or detecting ground conditions using data collected before and during the TBM operations and (2) designing and developing data-driven predictive models to predict the TBM state in real-time and adverse events such as structural defects, and anomalies.

PROJECT STATUS: For the first objective, we have completed large-scale UTI data collection, exploration, data processing, knowledge extraction, data analytics, and predictive analytics (Phases I and II). We are now refining the predictive model to improve results (Phase III). This work uses a big dataset from the Seattle Northlink project and is effective in predicting the soil composition. For the second objective, we used a big dataset from LA METRO to develop a predictive model for the status of the TBM and its performance in real-time (during the boring process). We have also developed our first model for adverse event prediction and anomaly detection based on deep neural networks.

MILESTONES ACCOMPLISHMENTS AND DATES: Objective I: Phase I completed in March 2018, Phase II completed in summer 2018, and Phase III is in progress. Objective II started in Fall 2018. Two initial predictive models have been developed for predicting the TBM state and detecting anomalies.
PLANNED ACTIVITIES: (1) Including a wide range of anomaly and adverse events for the predictive model; (2) Developing methods based on more complex deep learning models to account for more data elements and achieve higher accuracy levels; (3) Large-scale UTI data collection, exploration, pre-processing for the purpose of adverse event; (4) Building various predictive models based on combination of supervised and unsupervised machine learning techniques to achieve greater accuracy; (5) Enhancing data visualization; (6) Applying the proposed methods on other datasets; (7) Disseminating results.
PROJECT PERSONNEL: Mohammad Pourhomayoun (PI), Mehran Mazari (Co-PI), Luis Fisher (MS CS Student), Kabir Nagrecha (BS CS Student).

TITLE OF THE PROJECT: Resilience and sustainability of underground transportation infrastructure
SUMMARY: The goal of this study is to assess to what extent existing guidance for sustainable and resilient infrastructure design is appropriate for use with UTI. Based on this assessment, recommendations will be made for subsequent enhancements. The outcomes of this project will facilitate evaluation of UTI projects for resisting natural disasters, adapting infrastructure to the effects of climate change, and satisfying the various requirements of sustainability (environmental, social, and economic). This goal is in line with the objectives of the UTC-UTI and the broader goal of "Improving the durability and extending the life of transportation infrastructure" set by US DOT.
PROJECT STATUS: The following tasks have been completed: (a) a literature review in the areas of (i) guidance for transportation infrastructure, (ii) guidance for climate vulnerability assessments, (iii) rating systems, and (iv) underground-specific guidance; (b) an assessment of subway assets vulnerable to storm surge and sea level rise using the Climate Change & Extreme Weather Vulnerability Assessment and Scoring Tool (VAST) developed by the Federal Highway Administration; and (c) an assessment of the ISI Envision Rating System for a representative UTI project.
MILESTONES ACCOMPLISHMENTS AND DATES: The vulnerability assessment of underground assets using the VAST tool has been published and presented at the 2018 International Conference on Transportation and Development (July 2018). The literature review and the assessment of Envision have been completed and accepted for presentation and publication at the 2019 International Conference for Sustainable Infrastructure. The final paper has been finished, submitted, and accepted (April 2019).
PLANNED ACTIVITIES: The current ongoing activity is assessing the applicability of the LA Metro Resiliency Indicator Framework for UTI. This task will end the review and assessment of existing frameworks. Following this, the recommendations will be developed.
PROJECT PERSONNEL: Tonatiuh Rodriguez-Nikl (PI), Mehran Mazari (co-PI), new student TBD.

TITLE OF THE PROJECT: Continuous automatic detection of cracks in tunnels using machine learning and artificial intelligence techniques for safety monitoring
SUMMARY: Structural monitoring of the inner walls of a tunnel is important for safety, performance, liability, and cost. The goal of this project is to develop a fully automated system to perform continuous monitoring of tunnels during and after construction. The following aspects of this problem require further study: (a) a suitable technique for relevant data acquisition (this usually involves imaging the interior walls of the tunnel, but the exact method for doing this that is reliable, cost efficient, and easily automated is an open problem); (b) tools and techniques to acquire the data in an efficient and automated manner and communicate the information to proper processing center; (c) suitable techniques for post processing of acquired data to generate an intermediate observation space on which detection algorithms may be applied; (d) suitable algorithms and techniques for pattern detection and classification; (5) the software suite needed for data processing from post processed data to implement selected pattern detection and classification algorithms/techniques, assess their performance and develop recommendations.

PROJECT STATUS: A first, low-cost, image capture prototype was deployed and tested in 2017. Based on its performance a second prototype was developed using commercial, off the shelf equipment, including a DLSR camera with high intensity LED arrays and synchronized flash lights in 2018. The convolutional neural network (CNN) was trained based on the acquired image database achieving a 97.8% accuracy in automated detection of cracks and other blemishes. Acquired images need to be tagged with location information within the tunnel. Multiple approaches were studied for localization within tunnels and other underground infrastructure in the absence of any GPS, WiFi or any other beacon signal which may be used to define reference locations. We studied a promising approach for indoor localization using stereo cameras named visual Simultaneous Localization and Mapping (SLAM). The relevant systems were designed, developed and implemented in hardware and software using massively parallel Graphic Processing Units (GPU) from NVIDIA (Jetson TX2) and ZED stereo camera.
MILESTONES ACCOMPLISHMENTS AND DATES: Prototypes for crack detection were developed in 2017 and 2918. The Visual SLAM system was designed, developed, implemented and tested in both the 3rd floor of the Engineering building and in the field at the Griffith Park Tunnel, verifying functionality and the ability to provide real-time accurate relative localization in underground transportation infrastructure in absence of GPS or any other augmentation signal or system.
PLANNED ACTIVITIES: Continuation of the efforts in design and development of an inertial navigation system; system integration of the localization and data acquisition sub-systems for complete autonomous operation; exploration of design, development and implementation of autonomous electrified platforms for application to infrastructure monitoring.
PROJECT PERSONNEL: Fred Daneshgaran (PI), Marina Mondin (co-PI), Antonio Marangi, Nicola Bruno, and Fausto Lizzio, all students are from Politecnico Di Tornio, Turin, Italy (Visiting scholars at CSULA, all pursuing MS in Mechatronics).

TITLE OF THE PROJECT: Evaluating the use of recycled and sustainable materials in self-consolidating concrete for underground applications

SUMMARY: Self-Consolidating Concrete (SCC), also known as self-compacting concrete, is a type of hydraulic cement concrete that easily forms around the reinforcement without segregation. Design of an SCC mix is chosen based on either powder-type, viscosity modifying admixture-type, or a mixture of the two types depending on structural and constructional conditions, and material available. Due to the improved fresh properties of SCC, this concrete type is more favorable for precast sections that could be used in transportation infrastructure applications. The main objective of this study is to investigate the effect of fiber-reinforcement on fresh and hardened properties of the SCC. The fiber type and content in the SCC mix, affect the compressive strength, tensile strength and crack initiation and propagation. The improved mechanical properties of the fiber-reinforced SCC make it an alternative solution for pre-cast sections for transportation infrastructure applications compared to the conventional concrete. The other objectives of the research are: (a) review of literature to study the application of self-consolidating concrete for underground infrastructures, (b) evaluating fresh and hardened properties of self-consolidating concrete, (c) evaluating the use of recycled fibers to improve the properties of self-consolidating concrete, (d) investigating the use of sustainable materials (i.e. fly ash and slag) to reduce the amount of cementitious materials in self-consolidating concrete, and (e) evaluating the crack initiation and propagation related to properties of the self-consolidating concrete.
PROJECT STATUS: The project is in Phase II. Three sources of recycled fibers were identified and are being used in the mixture of SCC laboratory samples. Fiber-reinforced SCC beam samples are being prepared and evaluated for flexural strength. Fresh and hardened properties of fiber-reinforced SCCs are also being evaluated. Drying shrinkage and water absorption of SCC samples are being evaluated.
MILESTONES ACCOMPLISHMENTS AND DATES: Four papers from this project were submitted to Transportation Research Board annual meeting and ASCE conferences.

PLANNED ACTIVITIES: The laboratory testing and evaluation, as well as development of database and analytical models, will continue. Bulk resistivity tests are planned to be performed on fiber-reinforced SCC samples. Beam samples are being cured and will be evaluated for the flexural strength. The potential collaborations with DOT and other industry partners are planned.
PROJECT PERSONNEL: Mehran Mazari (PI), Tonatiuh Rodriguez-Nikl (co-PI), Keyur Dhawan (MS CE student), Siavash F. Aval (Research Associate).

Research at Lehigh University

TITLE OF THE PROJECT: Assessing and improving the resilience of highway and rail tunnels to blast and fire

SUMMARY: The project team is developing a new framework for evaluating the vulnerability of tunnel infrastructure to blast and fire hazards. Blast and fire are evaluated as separate hazards as well as cascading hazards (e.g. a fire following an intentional explosive detonation, or the deflagration of a fuel tanker due to an initial small fire) where appropriate. The resulting assessments can be used to prioritize and tailor mitigation strategies, systems, and placement to maximize risk reduction with available resources. The framework leverages several fast running analysis techniques for analyzing the effects of blast and fire on large structural systems – due to their computational efficiency, these methodologies can be used to evaluate the effects of blast and fire at a range of locations in large tunnels or among inventories of tunnels via large batches of simulations using randomly selected inputs. This effort is computationally focused, and funds dedicated to this project are used primarily for student support.
PROJECT STATUS: Computational efforts focused on blast effects have resulted in the creation of a conservative method of predicting spall and breach of a concrete tunnel lining from a vehicle-borne threat. The model leverages experimental data from accepted blast criteria, and additionally employs Rhinoceros and Grasshopper for calculation and visualization. The intermediate approach has been validated against computationally intensive finite element modelling using LS-DYNA for several typical tunnel prototypes. This work was presented at the Transportation Research Board (TRB) Conference in Washington, D.C. in January 2018, and published in the Transportation Research Record in September of 2018. In a similar manner, Rhinoceros and Grasshopper have been utilized further to create a visual tool for calculating thermal demands on a tunnel liner for given fire sizes. Accepted structural fire design criteria are leveraged in the intermediate modelling process. Again, computationally intensive modelling with the Fire Dynamics Simulator (FDS) software package is utilized for validation of the intermediate approach. FDS models are compared against existing experimental work by others for validation of applicable fire hazard effects in the tunnel environment. This work was presented at the 10th International Conference for Structures in Fire (Sif18) in Belfast, Northern Ireland in June 2018 as well as the TRB Annual Meeting in Washington, DC in January 2019. A manuscript was submitted in February 2019 to the Fire Safety Journal and accepted in September 2019 and published. Ongoing efforts are being focused on analysis of representative tunnels subject to blast loads using numerical models to examine the resilience of ancillary structural components of the tunnel such as the false ceiling. A journal publication is being developed as a result of the effort. Another paper is under development which consists of a comprehensive probability-based framework to examine the cost/benefit performance of various size vehicle fire hazards.
MILESTONE ACCOMPLISHMENTS AND DATES: (1) Literature review and database – May 2017. (2) Establishment of tunnel prototypes – June 2017, (3) Evaluation of prototypes to near field blast effects and conference summary paper – August 2017, (4) Presented rapid blast damage prediction tool at TRB Annual Meeting – January 2018, (5) Acceptance of blast paper to Journal of the TRB – March 2018, (6) Evaluation of prototypes to radiation and convection from severe fire and summary conference paper – March 2018, (7) Presentation at SiF18 June 2018, (8) Refinement of fire models to account for variation in tunnel geometry (rectangular, horseshoe, round), mesh sensitivity, and fire size – June to August 2018,

(9) Submitted TRB paper on predictions for fire induced spall - August 2018, (10) Developed estimates of gas pressure overload generated from accidental explosions in tunnels - September 2018 through March 2019, (11) Presented rapid fire damage assessment tool at TRB Annual Meeting - January 2019, (12) Awarded $30,000 from the Pennsylvania Infrastructure Technology Alliance (PITA.org) to leverage UTC-UTI funds toward the investigation of blast effects on false ceilings in tunnels – January 2019. (13) Submitted journal manuscript to Fire Safety Journal regarding the rapid-fire damage assessment tool – February 2019. (14) Acquired sample tunnel structural drawings from DOT collaborators from Oregon and Pennsylvania January 2019. (15) TRB paper submission on probabilistic framework for fire hazard assessment August 2019. (16) Published Fire Safety journal submission September 2019

PLANNED ACTIVITIES: (1) Submit publication on the performance of tunnel false ceilings subjected to blast pressure demands from VBIED and accidental explosive events. (2) Improve the semi-empirical damage prediction approach used in the current fire induced tunnel liner damage framework. (3) Submit a journal publication on the probabilistic methodology for conducting a resilience assessment of tunnel systems to fire events and conduct a sample analysis. (4) Conduct a probabilistic blast hazard assessment of tunnel liner and false ceilings, this will be executed in task 2 of year 4.

PROJECT PERSONNEL: Post-doctoral researcher Dr. Fengtao Bai (appointment completed March 31, 2018), M.Sc. student Kyle Root (graduated September 1, 2018), Ph.D. student Qi Guo, Ph.D. student Aerik Carlton, M.Sc. student Ziyan Ouyang, Faculty Dr. Spencer Quiel and Dr. Clay Naito.

TITLE OF THE PROJECT: Development of a blast and fire-resistant structural tunnel liner

SUMMARY: A study of concrete liner segments is conducted to develop a design approach that provides improved resistance to blast and fire effects in tunnels. The scope of blast and fire demands to be considered have been determined through preliminary analytical evaluations of a set of tunnel types subject to a range of demands (i.e., small/large Improvised explosive device, vehicle fire / fuel transport vehicle fire). Preliminary designs for typical reinforced concrete liners have been numerically evaluated for a range of expected load severities and validated for a limited number of cases using previously published data. Preliminary experimental investigation of the prototype liner is currently being conducted to verify resistance to close-in blast and fire exposure. Testing will be conducted at facilities available at Lehigh University and the Colorado School of Mines. Blast testing will focus on the development of shock-induced cracking and breach through the liner thickness against a known substrate (soil, rock, water, or grout). Fire testing will focus on the development and severity of concrete spall damage experienced by the concrete liner while restrained against thermal expansion.

PROJECT STATUS: An extensive numerical evaluation of concrete lining under blast loading is underway. LS-DYNA is employed to develop a deeper understanding of the failure mechanisms that develop in response to close-in blast loading. Parameters effecting damage for a given charge size are being numerically evaluated: backfill material, liner thickness and strength. The results of these analyses are being used to design experiments that will be performed at the Colorado School of Mines in collaboration with CSM faculty and students. In addition, an investigation of gas pressure increases due to a range of blast hazards is being explored, particularly its effects on false ceilings and ventilation systems. The effect of blast on these systems may initiate their failure and collapse, thus endangering tunnel occupant safety and inducing larger losses of functionality.

The behavior of concrete lining under fire conditions is being investigated both numerically and experimentally. An experimental program was initiated to investigate the effect of pertinent parameters on the propensity of thermal spalling, including rebar density, applied axial stress, and magnitude of thermal exposure. Fabrication of the experimental test set up has been completed. The test setup has been calibrated, and preliminary tests have been performed. Test data will be coupled with the computational models to examine the growth of pore pressure as well as mechanical stresses through the thickness of the panel in relation to the fire severity. Preliminary spalling evaluations have been integrated

with the total damage mapping tool developed from the Lehigh team's other UTC-UTI project, which will be capable of conservatively predicting tunnel liner damage for a given fire event.

A conference call was held on August/21/2018 with seven state DOT representatives from the AASHTO T20 committee to discuss the current progress of this project and identify related topics of interest. The committee members highlighted several areas of research interest, including the blast and fire resistance of false ceiling and ventilation structures as well as tiles and other coatings applied to the tunnel liner. The Lehigh team is actively incorporating the T20 guidance into their planned research and has been receiving information and feedback from several members of this group.

This project is at completion and final milestones are being completed in the form of reports and papers. Our 2018 TRB paper provided a conservative numerical examination of blast-induced breach and spall damage – the results indicated that damage became significant only at higher blast threat sizes. Also, a numerical study of the interaction of the tunnel liner with non-rigid substrate indicated that blast-induced damage for large threat sizes could only be mitigated for substrate stiffnesses that are lower than those associated with realistic subsurface soil and rock conditions. The research team then began to focus on the blast resistance of false ceiling structures which are used to separate the main passageway from ventilation and mechanical passages overhead. These structures are significantly weaker than the liner and are very susceptible to blast-induced damage and collapse at relatively modest threat sizes. Based on these results, subsequent large-scale blast testing of a substrate-backed liner are not currently being pursued since their potential results may not be worth the significant investment that would be required. The false ceilings structures have such low blast resistance that large-scale blast testing of those components is also not warranted. Experimental resources are being refocused on the investigation of fire-induced damage on the tunnel liner, which may occur via either spalling or permanent losses of strength and stiffness, which might be less visible but problematic to the life cycle of the tunnel.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Literature review and database- May 2017. (2) Fire test matrix – June 2017. (3) Initiate numerical modeling of thermal effects – June 2017. (4) Developed test matrix and experimental research plan – October 2017, (5) Fabrication of phase 1 test specimens completed – January 2018, (6) Test setup developed and completed – March 2018. (7) Conference call with Prof. Jurgen Brune and his research team for preliminary discussion of blast testing at CSM underground facilities – July 2018. (8) TRB submission developed from preliminary numerical evaluations of spalling in combination with the damage mapping tool – August 2018. (9) Conference call with T20 members to discuss related topics of interest to be incorporated into the current research program – August 2018. (10) Calibrations performed for fire-induced spalling test setup at Lehigh's ATLSS Lab – September 2018. (11) Enhancements made to fire-induced spalling test setup to increase the range of fire exposure for larger events – March 2019. (12) A test series is nearing completion which correlate fire induced spall with moisture content and surface flux September 2019. (13) Numerical modeling of the test panels using Abaqus and Safir have been validated September 2019.

PLANNED ACTIVITIES: (1) Develop journal publication focused on the spall damage mechanism due to fire hazard using physical concrete spall tests and numerical simulation. (2) Conduct parametric experimental investigation of panel properties and surfaces to assess fire induced spall performance of liner segments to be conducted in Task 1 of year 4 effort. (3) Summarize blast sensitivity study to illustrate the influence of substrate on blast damage of liners as a UTC report.

PROJECT PERSONNEL: Post-doctoral researcher Dr. Fengtao Bai (appointment completed March 31, 2018), M.Sc. student Kyle Root (graduated September 2018), Ph.D. student Qi Guo, Ph.D. student Aerik Carlton, M.Sc. student Ziyan Ouyang (started September 2018), Faculty Dr. Clay Naito and Dr. Spencer Quiel, an offer was made to bring on a new Ph.D. student starting in July 2019. The student declined the offer.

1.2.2 Student Activities[i]

UTC-UTI continued to actively engage graduate and undergraduate students in its research, educational and outreach activities. Highlights of UTC-UTI student-related activities for this reporting period include:

a) A total of 33 students (21 PhD & MS, and 12 BS) are funded by UTC-UTI. Of which 15 (11 PhD & MS, and 4 BS) are working at CSM, 10 (7 MS and 3 BS) at CSULA, and 8 (3 PhD & MS, and 5 BS) at Lehigh. All graduate students actively worked on their thesis and dissertations and are progressing towards the completion of their degrees. 12 REU (Research Experiences for Undergraduate) students assisted the graduate students in their research. Students participated in all aspects research and outreach of the including design of experiments, computational modeling, data analysis, field surveys, project presentations and report writing. One MS student at CSM graduated in Spring 2019.
b) UTC-UTI students co-authored papers and participated and made presentations in several conferences including the *2019 Data Science Workshop at UC Irvine, 2019 Cal State LA DIRECT STEM Workshop, Rapid Excavation and Tunneling Conference in Chicago in June 2019, Association of Environmental and Engineering Geologists 2019 Annual Conference in Asheville, NC, September 2019, and World Tunnels Congress, Naples, Italy, May 3-8, 2019.*
c) Approximately 60-80 students each time have participated in UTC-UTI co-sponsored "*Underground Lunch and Learn*" Seminars. The lectures were given by leading experts, practitioners and researchers in the industry and academe, and provided good venue for interactions between lecturers and students.
d) 22 CSM students attended the Rapid Excavation and Tunneling Conference in Chicago in June 2019. Three CSM students were co-authors on papers and presented at the conference.
e) 14 CSM graduate students completed a design project on the LA Westside transit tunnel project in April/May as part of the Underground Construction Engineering in Soft Ground course. They designed the liner, assessed building deformation and developed TBM face pressure calculations along the alignment. The students presented their findings to LA Metro, contractor personnel, and design personnel from the project during a two-day site visit April 29-30, 2019.
f) Three graduate students and two undergraduate students were involved in data gathering in connection with the engineering feasibility study of the future extension of the EJMT.
g) One CSM Ph.D. student collaborated with Seequent, developers of the Leapfrog implicit geologic modeling software for automated assessment of geologic model uncertainty. Research done by the student will be implement in Leapfrog as part of UCT-UTI's T2 plan.
h) A CSM PhD student continued to collaborate with CDOT on a study of the resilience of transportation tunnels including the Eisenhower-Johnson Memorial Tunnel and the Hanging Lake Tunnel in Colorado.
i) Two Cal State LA students were selected for 2020 TRB Minority Fellowship award.
j) Two Cal State LA students were selected to receive transportation conference award from California Transportation Foundation.
k) CSM PhD student Ashton Krajnovich is the recipient of the Lemke Scholar Award.

1.2.3 Outreach Activities

a) UTC-UTI co-sponsored and UTC-UTI PI Reza Hedayat directed the *Grouting and Ground Improvement Short Course*. This 3.5-day short course was offered on May 13-16, 2019 and covered engineering, equipment, materials and methods for grouting and ground modification used in civil and geotechnical engineering, underground construction, tunneling and mining. It included topics in engineering, equipment, materials and methods for grouting and ground modifications used on various types of projects. A total of 90 industry speakers and participants attended this short course. Field demonstrations of compaction grouting, drilling and grouting equipment, packers, permeation

grouting (sand columns), cellular concrete, product demonstrations, instrumentation were included in the program.

b) UTC-UTI co-sponsored the "*Underground Lunch and Learn*" seminar series related to underground transportation infrastructure. The seminars were widely attended by CSM faculty, researchers and students.
c) UTC-UTI researchers continued to actively participate in several Technical Committees in AASHTO, TRB, ASCE, ARMA and other professional organizations.
d) Dr. Mike Mooney UTC-UTI Associate Director launched a *Teach the Professors program for Civil Dr. Mooney of CSM launched a Teach the Professors program for Civil Underground the academic year 2018-19*. Seven professors from Civil Engineering programs around the US: (1) attended the North American Tunneling conference in Washington DC in June 2018, (2) assisted in underground-driven civil engineering curriculum, and (3) will implement the curriculum in their classrooms during Spring 2019.
e) UTC-UTI PI Reza Hedayat is chairing the tunneling committee of the American Rock Mechanics Association (ARMA) and the first brainstorming meeting for establishing this committee was held in June 2019 during the ARMA Conference.
f) CSULA PIs gave presentations at the Transportation Research Board Annual Meeting and ASCE Conference, Cal State LA Research Symposium, University of Southern California Research Seminar, and the Hispanic Engineer National Achievement Awards Corporation (HENAAC) Conference.
g) CSULA has been reaching out to LA Metro Rail and collected new big datasets for training modeling and validating the developed algorithms.

1.2.4 Leveraging UTC-UTI Funds [i]

Extensive efforts have been made by UTC-UTI PIs to engage the industry, State DOTs and other partners in leveraging UTC-UTI funds to generate additional funding and cost-match to support the research agenda of the Center. Industrial and State DOT co-funding and cost-matching ensure that that UTC-UTI research projects are of interest and relevance to industry and practice.

a) CDOT has provided help from project personnel and extensive data on the daily operation and maintenance of the Eisenhower-Johnson Memorial Tunnel (EJMT) and Hanging Lake Tunnel along I-70 in connection with UTC-UTI's research on the operational resilience of tunnels. The project team continued to meet and discuss with the CDOT tunnel office on the potential to further mine and enhance CDOT'S CTMS (Colorado Transportation Management Software) database.
b) CDOT has provided $100,000, project personnel and extensive historical data on the geological studies, design and construction of the EJMT as part CSM UTC-UTI's engineering feasibility study of the future extension of EJMT.
c) Lehigh University was awarded $30,000 from the Pennsylvania Infrastructure Technology Alliance (PITA.org) to leverage UTC-UTI funds in collaboration with Pennsylvania Department of Transportation toward the investigation of blast effects on false ceilings in tunnels.
d) Seequent, Agisoft and Maptek provided licenses for software in support of UTC-UTIs research on "Adaptive, Predictive 3D Geologic Modeling for Hard Rock Tunneling."
e) CSULA leveraged UTC-UTI funds to develop and implement Artificial Intelligence algorithms for automatic pattern classification and autonomous indoor navigation technology. These advancements have led to applications in autonomous robotics and autonomous systems being developed by a startup company founded by Dr. Daneshgaran and an EX Electrical Engineering student of his who now holds a leading position in Electrified Vehicle's industry
f) Tongji University in China provided valuable data on the construction of MuZhai Ling Tunnel in China, and extensive data on the operation and maintenance of subway tunnels in Shanghai, China.

g) Data sets and project personnel from two tunneling projects, LA Metro Regional Connector and Seattle Sound Transit, contributed extensively to this project during this period.
h) Skanska Construction Company provided $13,500 to support PhD student Haotian Zhang's living expenses in carrying out his field research on the LA project site.
i) Jay Dee Contractors provided in-kind support valued at $87,500 for the Seattle Northlink project analysis.
j) Lane Construction company is providing access to extraordinary instrumented segmental lining load processes and data to UTC-UTI research on "Data-Driven Risk Mitigation of Cross Passage and Cavern Deformation."
k) RAMAX LLC has provided free use of their waterjet laboratory, equipment and staff. The estimated cost of $50,000 is provided as cost match to a research project funded by UTC-UTI.
l) CSM IET Waterjet Foundation has provided more than $5,000 support for travel of UTC-UTI researchers and students.

1.2.5 Faculty and Researcher Accomplishments[i]

UTC-UTI faculty and researchers continued to achieve distinctions in their fields of work during this reporting period. Examples include:

a) From February 2019 to February 2020, Hugh Miller (UTC-UIT PI) serves as the President of the Society for Mining, Metallurgy, and Exploration (SME), which serves and represents the Underground Construction Association (UCA) Division of SME. During this reporting period, Hugh Miller has attended numerous tunneling and underground construction conferences and meetings, including the *World Tunneling Congress*, the *ITA Annual Meeting*, and the *SME Rapid Excavation and Tunneling Conference*.
b) Dr. Marte Gutierrez, UTC-UTI Director, was Keynote Lecturer in the *8th International Conference on Discrete Element Methods (DEM8)*, July 21-26, 2019, at the University of Twente, The Netherlands. He also gave invited presentations at two different universities. He served as member of the Organizing Committee of the International Symposium on SPH and Other Particle-Based Continuum Methods and their Applications in Geomechanics, Vienna, Austria, September 9-13, 2019. He continued to serve in the editorial board of five international journals.
c) Professor Mike Mooney delivered a lecture "Artificial Intelligence and Physical Model Based Performance Prediction of EPB TBM Tunneling" at Waseda University, Tokyo, on April 15, 2019. He also delivered a presentation on "Research and Development in Underground at Colorado School of Mines" at Sapienza University, Rome Italy, on May 2, 2019.
d) CSULA PI Mohammad Pourhomayoun was recognized by the CSULA Office of Graduate Studies for the Outstanding Mentorship of Graduate Students in the Areas of Research, Scholarship and Creative Activity for 2018-2019.
e) CSULA PI Mehran Mazari was appointed as: i) Co-Chair of Long Term Pavement Performance (LTPP) Data Analysis Contest subcommittee of Highway Pavement Committee – ASCE Transportation and Development Institute; ii) Member of ASCE-T&DI Sustainable Transportation Committee; iii) Handling Editor for the Journal Transportation Research Record (TRR) of the Transportation Research Board (TRB); and iv) Faculty Director of the newly established Sikand Center for Sustainable and Intelligent Infrastructure (SITI-Center) at the College of Engineering, Computer Science, and Technology at Cal State LA.
f) Cal State LA was awarded for the 2019 National Summer Transportation Institute
g) Drs. Clay Naito and Spencer Quiel at Lehigh University continued to actively publish papers in journal and conference proceedings, and to make presentations at different venues to disseminate research results. Dr. Naito served as member of American Concrete Institute Committee 533 Precast Panels.

2. PRODUCTS

2.1 Publications, conference papers, and presentations.

Representative publications from UTC-UTI faculty, researchers and students from the last reporting period are listed below. A complete list of UTC-UTI publications, reports and presentations, and their copies will be posted at: https://zenodo.org/communities/utc-uti/.

Presentations:
UTC-UTI organized a session on Underground Transportation Infrastructure as part of CSM's Tunneling Fundamentals, Practice and Innovations Annual Short Course on October 17, 2019. Presentations from this session are posted in: Zenodo. https://zenodo.org/record/3489755#.XaToCUZKjZs

Selected Journal Publications:

Bai, F., Guo, Q., Root, K., Naito, C., Quiel, S. (2019). Blast Vulnerability Assessment of Road Tunnels with Reinforced Concrete Liners, Transportation Research Record, Journal of the Transportation Research Board, Manuscript Number: 18-05880, September 28, 2018.

Daneshgaran, F., Zacheo, L., Di Stasio, F., Mondin, M. (2019). Use of Deep Learning for Automatic Detection of Cracks in Tunnels: Prototype-2 Developed in the 2017–2018 Time Period, Transportation Research Record, Journal of the Transportation Research Board, May 3, 2019.

Guo, Q., Root, K., Carlton, A., Quiel, S., Naito, C. (2019). Framework for Rapid Prediction of Fire-Induced Heat Flux on Concrete Tunnel Liners with Curved Ceilings. Fire Safety Journal, Vol. 109, Oct. 2019.

Hampton, J. Gutierrez, M. and Frash, L. (2019). Predictions of Macro-Scale Fracture Geometries from Acoustic Emission Point Cloud Data in A Hydraulic Fracturing Experiment. Journal of Petroleum Exploration and Production Technology, Vol. 9(2), pp. 1175–1184.

Kamali-Asl, A., Bijay KC, Ghazanfari, E., Hedayat, A. (2019). Flow-induced alterations of ultrasonic signatures and fracture aperture under constant state-of-stress in a single-fractured rock. Geophysics, 84(4), WA115-125.

Katsuki, D., Gutierrez, M. and Almrabat, A. (2019). Stress Dependent Shear Wave Splitting and Permeability in Fractured Porous Rock. Journal of Rock Mechanics and Geotechnical Engineering, Vol. 11, pp. 1-11.

Oreste, P., Hedayat, A., and Spagnoli, G. (2019). Effect of Gravity of the Plastic Zones on the Behavior of Supports in Very Deep Tunnels Excavated in Rock Masses. International Journal of Geomechanics 19 (9).

Shirole, D., Hedayat, A., and Walton, G. (2019). Experimental Relationship Between Ultrasonic Attenuation and Surface Strains in Prismatic Rock Specimens, Journal of Geophysical Research - Solid Earth, 124(6), 5770-5793.

Tomac, I. and Gutierrez, M. (2019). Micromechanics of Hydro-Thermo-Mechanical Processes in Rock Accounting for Thermal Convection. Journal of Engineering Mechanics, ASCE, 145(8).

Wnuk, K., Walton, G. and Zhou, W. (2019). Four-dimensional Filtering of InSAR Persistent Scatterers Elucidates Subsidence Induced by Tunnel Excavation in the Sri Lankan Highlands. Journal of Applied Remote Sensing, 13(3).

Zhang, G. Li, M., Gutierrez, M. and Chao, K. (2019). Hydrodynamic and Mechanical Behavior of Multi-Particle Confined Between Two Parallel Plates. Advanced Powder Technology, Vol. 30(2), pp. 439-450.

Selected Conference Papers and Presentations:

Arora, K., Gutierrez, M., and Hedayat, A. (2019). Experimental Setup for Studying Tunnels in Squeezing Ground Conditions. 2019 ITA-AITES World Tunnel Congress, Naples, Italy, May 3-8, 2019.

Butt, A., Fragomeni, C., Hedayat, A., and Tudisco, E. (2019). Applicability of Ultrasonic Tomographic Technique for Progressive Damage Evaluation in Prismatic Rock Specimen. 53rd US Rock Mechanics/Geomechanics Symposium, Brooklyn, New York, June 23-26, 2019.

Epel, T, Mooney, MA, and Gutierrez, M. Liner Load Estimation for Pressure Balance Shield TBM Tunnel Projects, Proc. Rapid Tunneling & Excavation Conference, Chicago, IL, June 16-19, 2019.

Fathi, A., Mazari, M., Saghafi, M. (2019). Multivariate Global Sensitivity Analysis of Shallow Foundations Response under Controlled Rocking. Geo-Congress, American Society of Civil Engineers, Pittsburgh, PA.

Fathi, A., Tirado, C., Mazari, M., Nazarian, S. (2019). Models for Estimation of Moduli of Unbound Materials with Lightweight Deflectometer. Geo-Congress, American Society of Civil Engineers, Pittsburgh, PA.

Gheibi, A., and Hedayat, A. (2019). Ultrasonic precursors to shear failure of rock joints in Gosford sandstone with rough contact surfaces. 53rd US Rock Mechanics/Geomechanics Symposium, Brooklyn, New York, June 23-26, 2019.

Grasmick, JG and Mooney, MA. Probabilistic Risk Maps for the Construction of Tunnels in Soft Ground based on Spatial Uncertainty Modeling. 2019 ITA-AITES World Tunnel Congress, Naples, Italy, May 3-8, 2019.

Gutierrez, M. and Hou, Z. (2019). Strain-Rate Dependent Pre-Failure, Failure and Post-Failure Behavior of Shale: Experiments and Modeling. Sixth EAGE Shale Workshop, Bordeaux, France, April 28 to May 1, 2019.

Gutierrez, M. and Muftah, M. (2019). DEM and Plasticity Modeling of the Stress-Strain Behavior of Granular Materials in the Strain Hardening and Softening Regimes. 8th International Conference on Discrete Element Methods, University of Twente, The Netherlands, July 21- 26, 2019 (**Keynote Lecture**).

Khetwal, S.S., Pei, S., Gutierrez, M. (2019). Operational Resilience of Traffic Tunnels: An example case study. 2019 ITA-AITES World Tunnel Congress, Naples, Italy, May 3-9, 2019.

Krajnovich, A., Zhou, W., and Gutierrez M. (2019) Uncertainty Assessment of Fault Zones in 3D Geologic Models of Mountain Tunnels, Association of Environmental and Engineering Geologists 2019 Annual Conference in Asheville, NC, September 2019.

Mazzia, V., Daneshgaran, F., Mondin, M. (2019). Use of Deep Learning for Automatic Detection of Cracks in Tunnels, 29th Italian Workshop on Neural Networks (WIRN), Vietri sulMare, Italy, June 2019

Miller, H.B. (2019). The Fundamentals of Resource Extraction, US Geologic Survey & U.S. Dept. of Commerce, Afghan Capacity Building, AGS & MoM, Istanbul, Turkey, June 24-30, 2019.

Miller, H.B. (2019). Mining Education: Challenges, Pitfalls & Opportunities. SME Colorado Mineral Processing Conference, Colorado Spring, CO, April 26, 2019 (**Invited Lecture**).

Mokhtari, S and Mooney, MA. Feasibility Study of EPB TBM Automation using Deep Learning, 2019 ITA-AITES World Tunnel Congress, Naples, Italy, May 3-8, 2019.

Packman, S., Lopez, S., Fathi, A., Mazari, M. (2019). Using Soil-Moisture Active Passive Satellite Data to Evaluate the Performance of Transportation Infrastructure Foundations–A Feasibility Study. Geo-Congress, American Society of Civil Engineers, Pittsburgh, PA.

Rodriguez-Nikl, T., Cedano, S., Martinez, E. and Ojeda, F. (2019). Predicted Slip of Ballasted Solar Arrays on Angled Roofs Due to Seismic Motion. Structures Congress 2019.

2.2 Website(s) or other Internet site(s)

The UTC-UTI website, which is continuously being updated, can be found at: http://underground.mines.edu/utc-uti. Archiving and dissemination are hosted by Zenodo at: https://zenodo.org/communities/utc-uti/. Copies of the Program Progress Performance Reports (or Semi-Annual Project Reports), meeting presentation slides, publications and technical reports from UTC-UTI

can be downloaded from this site. Since the launch of the Zenodo archiving and dissemination cite, UTC-UTI reports and publications have been viewed 463 times and downloaded 1013 times.

2.3 Technologies or techniques

Several technologies and techniques are currently in development including: data-driven back-analysis procedures; functional reliability of tunnels during operation; probabilistic methods for rock mass classification and tunnel design; scaled modeling of tunnel squeezing; using DC resistivity to image ahead of tunnel excavations; applications of Data Science, Big Data Analytics, Machine Learning and AI construction and maintenance of UTIs; continuous automatic detection of cracks in tunnels; use of recycled materials; establishing resilience and sustainability metrics for UTIs; improving resilience of UTIs to extreme events of fire and blasts, and through the use of resistant materials; development of adaptive and predictive 3D geologic models; use of InSAR to monitor ground surface deformations above underground excavations; shotcrete removal by waterjet; and new tunnel excavation methods including use of microwave.

Specific technological developments include: 1) Development of an input-based, uncertainty assessment technique designed for 3D geologic modeling of fault zones intersecting mountain tunnels, undertaken as a collaborative effort between the researchers and Seequent. 2) In terms of resilience of UTIs to extreme events of fire and blasts, rapid fire and blast assessment tools were developed using Rhino/Grasshopper visual programing platform. Preliminary discussions were carried out with Thornton Tomasetti in Philadelphia to examine utilization in industry evaluation efforts.

2.4 Inventions, patent applications, and/or licenses

Nothing to report for the reporting period.

2.5 Other products

Nothing to report for the reporting period.

3. PARTICIPANTS AND COLLABORATING ORGANIZATIONS

3.1 Organizations which have been involved with UTC-UTI

a) Representatives from the following organizations are *members of the UTC-UTI Advisory Board*: 1) Colorado DOT (Denver, CO); 2) Federal Highway Administration (Washington, DC); 3) Mott MacDonald (Millburn, NJ); 4) Council of University Transportation Centers (Washington, DC); 5) Arup (New York, NY); 6) Penn DOT (Harrisburg, PA); 7) WSP/Parsons Brinckerhof (Chicago, IL and Washington DC); and 8) Tongji University (Shanghai, China).
b) The following organizations *have provided cash or in-kind cost-match to UTC-UTI projects*: 1) CDOT (Golden, CO); 2) RAMAX LLC (Lakewood, CO); 3) IET Waterjet Foundation (Golden, CO); 4) MapTek (Golden, CO); 5) Tongji University (Shanghai, China); 6) JayDee Contractors (Lakewood, CO); 7) LA Metro (Los Angeles, CA); 8) Skanska Construction Co. (Los Angeles, CA); 9) Seattle Sound Transit (Seattle, WA); 10) University of British Columbia (Vancouver, Canada); 11) Lane Corporation (Washington, DC); 12) Pennsylvania Infrastructure Technology Alliance (Pittsburgh, PA); 13) California State University Transportation Consortium (San Jose, CA); 14) Seequent (Christchurch, New Zealand).
c) Representatives from the following organizations have *given presentations in the UTC-UTI co-sponsored seminar series*: BGC Engineering (Golden, CO); Geosyntec Consultants (Atlanta, GA); Brieley Associates (Golden, CO); Kiewit (Omaha, NE); and Traylor Bros. (Bethesda, MD).

3.2 Have other collaborators or contacts been involved?

UTC-UTI has been in continuous contact with CDOT, industry and academe on potential collaborations and co-funding of UTC-UTI efforts. UTC-UTI is now working with CDOT on the engineering feasibility study of the Eisenhower-Johnson Memorial Tunnel. Different construction companies have provided access to valuable data from tunnel construction projects, and training, internship and employment opportunities for UTC-UTI students. Different software companies have provided free software licenses in support of UTC-UTI research efforts.

4. IMPACT

4.1 What is the impact on the development of the principal discipline(s) of the program?

The main research focus of UTC-UTI is the development and deployment of major improvements in the design, planning, construction, maintenance, operation, retrofit and expansion of underground transportation infrastructure to make them more durable and to extend their lifetime. These developments will be realized by moving away from largely empirical and tradition-based procedures to an intelligent and data-driven system that uses recent progress in condition monitoring, sensing and asset/performance assessment, as well as in new construction materials and technologies. Underground transportation projects require large budgets and long construction times. It is important to develop advanced technologies that will improve the durability and extend the life of underground transportation infrastructures to ensure that they function as intended for, recover investment costs, and avoid major problems that have often afflicted underground constructions. Research from UTC-UTI will lead to cost savings, decrease in construction times and site damages and loss of life, and reduction in the impact of underground construction to the natural and built environments, and eventually to increased safety, reliability, performance and sustainability of new and existing underground transportation infrastructures. UTC-UTI is now starting to meet its goals of providing impact on its focus areas.

4.2 What is the impact on other disciplines?

UTC-UTI's research agenda are interdisciplinary with contributions from and projected impact to the fields of Geotechnical Engineering, Geology and Geological Engineering, Geophysics, Material Science, Mining, Structural Engineering, Tunneling, and Transportation Engineering. In addition, UTC-UTI is also envisioned to be multidisciplinary and contribute to the fields of Data Science, Big Data Analytics, Information Technology, Visualization, Remote Sensing, Instrumentation, Machine Learning and Artificial Intelligence.

4.3 What is the impact on the development of human resources?

A total of 34 students and three postdocs were supported by UTC-UTI through 17 research projects. UTC-UTI also continued to hold outreach and recruiting initiatives aimed at encouraging K-12 and undergraduate students to pursue advanced degrees in STEM.

4.4 What is the impact on physical, institutional, and information resources at the university or other partner institutions?

Results from UTC-UTI are being widely disseminated and archived for long-term access using Zenodo, which is a publicly available data repository. Archived research results can help support future research in the area of Underground Transportation Infrastructure at partner institutions and the academe in general, and to promote technology transfer to the industry. Links to the archived results are actively promoted through our Center webpages including our archiving web page in Zenodo.

4.5 What is the impact on technology transfer?

UTC-UTI interacted with industrial and state DOT partners to provide mechanisms for stimulating technology transfer and turning research results directly into technological innovation. Technology transfer is being carried out in four ways:

a) Working with various components of the underground transportation industry (including Federal or State Transportation Agencies) through industry-funded, co-funded, cost-matched or collaborative research. Examples are: i) the engineering feasibility study of future extension of the Eisenhower-Johnson Memorial Tunnel which is co-funded by CDOT, ii) a study on resilience of traffic tunnels in Colorado in collaboration with CDOT; iii) investigation of blast effects on false ceilings in tunnels with support from Pennsylvania Infrastructure Technology Alliance and Pennsylvania DOT; and iv) study of the LA Metro Regional Connector and Seattle Northlink projects with various construction companies.

b) Sharing of innovations via continuing education (including short courses), seminars (including webinars), workshops. Examples are: 1) *Session on Underground Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course*, 2) *Teach the Professors program for Civil Underground*, and 3) *Grouting and Ground Improvement Short Course.* Other examples of direct technology transfer: i) implementation of research results in Seequent's Leapfrog computer program, and ii) contributing towards the setting up of a startup company for autonomous robotics and systems.

c) Training of students and personnel. Examples include embedding of UTC-UTI students in different projects and internships in construction companies.

d) Dissemination through publications of research in journals and conference proceedings, reports, and design manuals. All UTC-UTI publications are also disseminated through our archiving and dissemination website at Zenodo where publications have been viewed 463 times and downloaded 1013 times.

4.6 What is the impact on society beyond science and technology?

Currently, underground design, planning, construction and operation are primarily driven by technical and economic considerations. Often, for example, very little regard is given of their long-term impact on the environment and society in terms of natural resource depletion, environmental impact, and climate change. Sustainable approaches for underground construction should holistically account for economy, environment, and society. UTC-UTI considers both sustainability and resiliency as integral parts of an asset management plan and require collection of required data and the computation of truly quantitative metrics. Resilience and sustainability are complementary attributes of the underground infrastructure, and only the combination of both aspects can provide a truly comprehensive assessment of the quality of the underground infrastructure. UTC-UTI envisions to help promote economical, reliable and efficient intermodal transport as the key to helping uplift the condition of communities. This will be done via the advancement of development of equitable transport systems through integrated surface and subsurface planning and utilization for the infrastructure network. The overarching objective will be on improved quality of life (QOL) and quality of service (QOS) while building resiliency in all transportation projects. This objective will be achieved by advocating underground transportation systems that can move passengers faster, economically, conveniently, reliably and safely, and able to respond and recover fully and quickly from operational breakdowns, deterioration and extreme events.

5. CHANGES/PROBLEMS

Nothing to report.

---

[i] No direct or indirect DOT funds were used for international activities and travels.