UNIVERSITY TRANSPORTATION CENTER
FOR UNDERGROUND TRANSPORTATION INFRASTRUCTURE

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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 proposed 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 16 research projects (eight at CSM, four at CSULA and two 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. 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; (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.

PROJECT STATUS: (Obj. 1) The evaluation of liner loads monitored during Seattle Northlink tunnel construction has been completed. Our participation in the NEBT project liner load instrumentation has begun successfully. We will continue this work in conjunction with the NEBT project team. The assessment of liner design practice and comparison to measured loads is underway; the analysis has been completed for Northlink. (Obj. 2) The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is complete and 3D finite element modeling is nearing completion. (Obj. 3) Analysis of LA metro cavern excavation data coupled with real time computational modeling is ongoing. PhD student Haotian Zhang has been onsite in LA since July 2018 and is embedded with the construction project team.

MILESTONES ACCOMPLISHMENTS AND DATES: As of Oct 31, 2018: Objective 1 is 90% complete. One conference paper has been written and accepted, and a journal paper is under development. Objective 2 is 50% complete; one conference paper has been written and accepted. Objective 3 is 20% complete.

PLANNED ACTIVITIES: Seattle analysis will be complete in CY 2018. NEBT tunnel analysis will ramp up and LA Metro study will be completed in the next year.

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 look into 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 research team has developed a framework for data collection for critical roadway tunnels. The researchers have also visited two major tunnel facilities in CO and interviewed the staff from CDOT. It was discovered that there are no uniform or systematic procedures in existence currently to collect the needed functionality loss data. The project team has processed some historical operation record data from the CDOT tunnels to identify the gap between existing data status to the ideal data structure based on the developed framework.

MILESTONES ACCOMPLISHMENTS AND DATES: Intermediate findings have been summarized into papers and presentations and submitted to professional conferences and workshops. The development of a probabilistic simulation framework for tunnel infrastructure resilience has started

PLANNED ACTIVITIES: The research team plan to collaborate with an industry partner to enable collection of critical tunnel operation data through an automated procedure through the CTMS system used by CDOT (traditionally most of the CDOT critical tunnel operation data was collected manually on paper, while CTMS system was introduced a few years ago to automate traffic interruption event logging). The research team originally planned to conduct a survey study with DOT tunnel owners to identify the current status of operation data collection for tunnels. But the experience with CDOT seems to indicate that this is not an immediate need for the project. Thus, the researchers will focus on developing probabilistic framework for tunnel functionality loss analysis in the next reporting period.

PROJECT PERSONNEL: Dr. Shiling Pei, Dr. Marte Gutierrez and Sandeep Khetwal (PhD Student).

TITLE OF THE PROJECT: UTC-UTI Summer Tunnel Camps for Grade School Students

SUMMARY: The University Transportation Center for Underground Transportation Infrastructure (UTC-UTI) Tunnel Camp at Mines welcomed a total of 42 local 5th to 8th grade students to the CSM campus in two separate sessions in summer 2018. Each session of the camps featured five days of fun, hands-on activities that introduce students to underground construction, geotechnical engineering, construction materials, smart infrastructure and more. In collaboration with CDOT and the Mining Engineering Department, students also got to see tunnels in action through a tour of the Eisenhower Tunnel facility on Interstate 70 and the Edgar Experimental Mine in Idaho Springs. The Summer Camps were organized by Dr. Hongyan Liu (Teaching Associate Professor at CEE) and Dr. Priscilla Nelson (Professor and Head of the Mining Engineering Department and UTC-UTI's associate director for education, workforce development and diversity). Outreach and education are core parts of the mission of UTC-UTI.

PROJECT STATUS: Completed.

MILESTONES ACCOMPLISHMENTS AND DATES: Two tunnel camps were organized to host a total of 42 students. The first camp is from 7/9/2018-7/13/2018. The second camp is from 7/30/2018-8/3/2018.

PLANNED ACTIVITIES: The team at UTC-UTI designed the concept of the tunnel camp and planned 5 days of activities for students. The activities included introduction to tunnel infrastructure and its construction, basic engineering concepts in structural engineering and natural hazards, construction materials in tunnel construction, ground excavation and soil behavior, and mining and mineral extraction. The participating students were recruited from local middle schools through an application process. Special attention was put to ensure participation of students from groups under-represented in STEM.

PROJECT PERSONNEL: Dr. Hongyan Liu, Dr. Priscilla Nelson, undergraduate students and grade school teachers.

TITLE OF THE PROJECT: Uncertainly modeling and risk assessment in tunneling

SUMMARY: Uncertainty in rock mass properties is mainly caused by the inherently inhomogeneous nature of a rock mass itself. Assessment of rock mass quality without accounting for inherent uncertainty often leads to excessive conservatism in design and construction, resulting in a negative impact on overall design and construction processes; thus, accurate prediction of rock mass quality is critical to save project budgets and time. In this study, to advance rock mass quality assessment, a Q-based prediction model to assess probabilistic rock mass quality was proposed using a Markov chain technique with quantitatively characterized uncertainty. Based on the Markovian prediction approach, the statistical distribution of the Q-value was derived from arbitrary locations along a tunnel alignment using Monte Carlo simulations. In addition, an analytical calculation approach for the statistics (e.g., mean, standard deviation, and coefficient of variation) of the Q-value can be developed with given statistics of Q-parameters. In this study, the proposed prediction model and analytical calculation approach were applied to a case study of a raw water tunnel and validated by the actual registered Q-value. As a result, the proposed Q-based prediction model is capable of assessing the rock mass quality of unexcavated tunnel sections in a probabilistic way, thus serving as a supplement to geologic exploration and prospecting in the design of underground structures and tunnels. The results obtained from this study support that the proposed Q-based model is useful in evaluating excavation support strategies as well as construction time and cost, providing decision support for the optimization of tunnel design.

PROJECT STATUS: This project has started in January 2017: 1) Markov chain algorithm has been developed and used to analyze the rock mass quality of a Hong-Kong project, 2) One conference paper was published using a Hong-Kong project, 3) a few data sets were acquired from some tunnels, and 4) one peer-review journal paper is being prepared.

MILESTONES ACCOMPLISHMENTS AND DATES: A probabilistic Q-value of unexcavated tunnel sections were predicted, which agreed with the actual Q-value measured during construction (10/08/2018).

PLANNED ACTIVITIES: 1) Develop updating mechanics using Bayesian updating to use newly available Q-data during construction to update the Q-prediction model. 2) Investigate the predicted probabilistic Q-value using reliability-based method with deformation-based limit state function.

PROJECT PERSONNEL: Dr. Eunhye Kim, Dr. Marte Gutierrez, and Hui Lu (PhD student).

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

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 will be 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 is now fully operational in the laboratory and the analogue rock materials (mixtures of clay and cement) as rock like materials are being tested.

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.

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: Interferometric Synthetic Aperture Radar (InSAR) is an ideal tool for measuring surface deformation related to tunnel construction because of its ability to make measurements with sub-centimeter accuracy over large areas, as well as the availability of historical data needed to identify any pre-construction deformation. However, InSAR data is subject to many noise sources that must be removed in order to identify the desired signal. The project is in the process of collecting data for an in-depth analysis of the impacts that thermal expansion from buildings have on InSAR phase measurements. Access to data from a ground-based SAR survey during the TBM rescue of the Alaskan Way Viaduct Replacement Tunnel (SR-99) has been obtained. The ground-based data possesses extremely high temporal resolution, high enough to capture diurnal geodetic signals caused by thermal expansion and contraction of urban surfaces. These measured signals will be used as a basis to apply a thermal correction to satellite InSAR data acquired by the Cosmo-Skymed constellation. This method will be compared to other modeling based thermal correction methods to determine its effectiveness. Satellite and ground based InSAR data will also be compared to available GPS data to assess accuracy. If needed, the 4-D filtering method developed in our previous project may be applied as well. Surface deformation measured before, during, and after tunnel excavation allows us to make inferences about subsurface conditions and better characterize the impact of tunnel excavation on overlying ground and structural deformation.

PROJECT STATUS: Initial efforts to identify tunnel induced surface subsidence using traditional satellite InSAR began in May 2017. These initial efforts focused on applying Sentinel-1 data to urban settings, however, due to multiple obstacles, expected signals could not be identified. Current research efforts have shifted to identifying and modeling noise sources, then applying models to the data in order to elucidate suspected excavation induced settlements.

MILESTONES ACCOMPLISHMENTS AND DATES: Two presentations of this research were conducted in the past year including a presentation at the Association of Environmental and Engineering Geologists (AEG) Annual Meeting in September 2018 and a presentation at the 1st annual 2018 UTC-UTI Workshop.

PLANNED ACTIVITIES: Initial data processing has produced significant results, however there is a strong atmospheric component in our data, which impacts the absolute line of sight deformation measurements. We are currently using advanced InSAR processing techniques such as Persistent Scatterer InSAR (PSI) to identify and remove noise from atmosphere and digital elevation models. The feasibility of a novel 4-D filtering method is being tested to reduce noise introduced by atmospheric effects that are correlated in space but not in time. These results will be submitted for publication within the year. We then plan to investigate phase contributions from thermal expansion and contraction of buildings in urban areas through analysis of a ground-based SAR dataset collected in Seattle, WA during the SR-99 TBM stoppage. This information can then be applied to satellite InSAR data to correct for deformation induced by thermal changes.

PROJECT PERSONNEL: Dr. Wendy Zhou, 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 interpretation of some sparse initial investigations. As a predictive model of the true subsurface geology, the 3D geologic model has potential to aid in understanding these complex geologic settings and to provide a baseline for subsequent modeling. As tunneling progresses in a hard rock setting, information on the encountered geologic structures can be collected prior to installation of the final tunnel support. These new observations can be used to validate the current geologic model and to update the model to better account for previously unseen structures. For an existing tunnel, excavation data can aid in predicting how observed structures vary in the vicinity for potential expansions, while for a tunnel in progress excavation data can be used to adapt the model to unfolding conditions. Data digitization and spatial referencing can be combined with workflow-based modeling to improve the reproducibility of 3D geologic models. Bayesian statistics provide a convenient framework for making predictions with quantified uncertainty from a variety of sources (e.g., hard data and interpretations) and for updating the predictive model in light of new observations in the subsurface. The objectives of this project are: 1) To implement a data-driven, reproducible 3D geologic modeling workflow that predicts geologic structures along a tunnel alignment with quantified uncertainty. 2) To utilize additional information gathered while excavating to adapt the geologic model to the encountered geology in a Bayesian framework.

PROJECT STATUS: This project started in May 2017; literature review was completed in Spring 2018 and during Summer 2018 datasets from two tunneling projects were acquired and digitization is underway as of Fall 2018. Data are being processed to formulate reproducible 3D geologic models with appropriate geologic predictions to establish the baseline for adaptive modeling.

MILESTONES ACCOMPLISHMENTS AND DATES: A presentation on this research was given during the Tunneling Symposium at the 2018 AEG Annual Meeting in September 2018. Initial 3D geologic modeling of the MuZhaiLing Tunnel (MZL) in Gansu, China was completed in early October 2018 using the Leapfrog GEO implicit modeling software. Geologic field work at the Eisenhower Johnson Memorial Tunnels (EJMT)

in Colorado was completed in September 2018, including drone photogrammetry of rock outcrops and verification of historic mapping and rock sample classifications.

PLANNED ACTIVITIES: 1) Digitization and modeling of historic, geologic data from the EJMT. 2) Formulation and implementation of Bayesian predictive models of geologic conditions combining preliminary investigation and unfolding excavation data along existing and in-progress tunnel alignments. The predictive models will focus on extrapolation of known-continuous structures and adaptive drive-by-drive predictions.

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. In particular, 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 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 the purpose of better understanding the potential value to tunneling operations. The resulting data shows that DC resistivity is capable of detecting hazards in front of a TBM.

PROJECT STATUS: This project started in September 2017 as an MS graduate research study. Most laboratory experiments have been completed as of Spring 2018 and numerical modelling is underway to cross-validate experimental results.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Determination through laboratory measurements that electrodes from a DC resistivity system must be placed into probeholes 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).

PLANNED ACTIVITIES: Research work of the upcoming half-year will consist of further numerical simulations to confirm that experimental and theoretical results are consistent. Once this cross-validation is complete, the geophysical software will be used to simulate and examine other DC resistivity acquisition scenarios during tunneling that are challenging to test in the lab or in the field. Long term activities will consist of carrying out field experiments and developing algorithms to rapidly interpret the data during underground construction in real-time.

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 tunnel liners, this research seeks to develop a unique system that utilizes high pressure waterjet technology as the primary excavation tool. Building upon the success

of previous CSM research activities in underground rock scaling and scarification, qualitative evidence derived during empiric testing indicates that waterjets are capable of selectively removing damaged areas of support liners without structurally compromising the intact material adjacent to the area being repaired. The primary research objective is to quantitatively compare the damage caused to the surrounding structural liner and rock substrate by both conventional impact hammers and waterjet excavation methods during empiric cutting tests. Test panels were constructed using a shotcrete simulant overlaying wire mesh and a reinforced concrete substrate. The panels were then scanned with ground penetrating radar (GPR) before and after excavation to delineate fractures and possible delamination between the shotcrete and concrete substrate, as well as with the rebar/wire mesh. During mechanical and waterjet excavation, vibration data was also collected. An analysis of the vibration data showed approximately an order of magnitude reduction in acceleration during cutting for the waterjet system. GPR data collection was recently complete and the analysis is currently in progress. Additional physical inspection of the test panels will be completed for the final report. Preliminary results strongly indicate that waterjet shotcrete removal causes significantly less collateral damage to adjacent material and the delamination between the shotcrete and the substrate.

PROJECT STATUS: All mechanical and waterjet shotcrete cutting tests were conducted over the last 5 months and were completed in late August 2018. Vibration data collected during the cutting tests showed that waterjet excavation typically produced accelerations an order of magnitude smaller than mechanical excavation. Test panels were scanned with ground penetrating radar (GPR) before and after excavation. The GPR data analysis and related physical inspection are still in progress. The final report is currently being written and should be completed by December 14, 2018.

MILESTONES ACCOMPLISHMENTS AND DATES: 1) Completion of the testing methodology and design of the experimental system and test panels (August 2017), 2) Completion of the Laboratory Setups, including pumps, fluid handling system, test stands, and motion control system (December 2017). 3) Final fabrication and instrumentation of the test panels has been completed in March 2018. 4) Mechanical excavation of the test panels was completed (May 2018). 5) Waterjet excavation of test panels was completed at the RAMAX laboratory in California (August 2018). 6) Vibration data analysis has also been complete (September 2018). 7) All required GPR scans are finished (October 2018). 8) Final data analysis and the writing of the final project report is scheduled for completion by December 2018.

PLANNED ACTIVITIES: During the next three months, the GPR data will be analyzed and the final report will be completed and submitted. After the completion of the project, the results will be published in several journals and conferences. The two PhD students who have worked on the project, Erik Charrier and Josef Bourgeois, will present the results at the 2019 SME Annual Meeting and the 2019 TRB Annual Meeting, respectively. It is the intent of the project investigators to use the results of this research to solicit additional support to advance the scope of this research, including field testing. Josef Bourgeois will also use the data to supplement his PhD research project in pursuit of fulfilling his graduation requirements.

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

Research at California State University Los Angeles

TITLE OF THE PROJECT: Applications of Data Science and Big Data Analytics in Underground Transportation Infrastructure

SUMMARY: This research project focuses on the applications of data science, predictive analytics, and big data analytics in the construction, maintenance and performance of the underground transportation

infrastructure. 1) The first objective is to develop advanced data mining and novel machine learning based methods for predicting or detecting ground conditions using the data collected before and during the TBM operations. The three phases of this objective are (I) large-scale UTI data collection, exploration, and data processing; (II) knowledge extraction, data analytics, and predictive analytics; and (III) refining the prediction methods, data visualizations and data storage. 2) The second objective is to design and develop data-driven predictive models that can predict adverse events in UTI such as structural defects (e.g. cracks), and anomalies (e.g. hitting a solid object such as metal or rock during boring).

PROJECT STATUS: This project started in June 2017. Phase I and Phase II of the first objective are compete. We used a big dataset from a recent tunneling project and developed a new efficient prediction technique based on an advanced Deep Recurrent Neural Network (RNN). The method is very effective in predicting the composition of soil and specifications of ground. We have started Phase III. The latest results will be presented in TRB 2019 and also in the UTC-UTI workshop in Oct. 2018. As for the second objective, we have recently started large-scale UTI data collection, exploration, pre-processing for the purpose of adverse event prediction.

MILESTONES ACCOMPLISHMENTS AND DATES: Objective I, Phase I completed in March 2018, Phase II completed in summer 2018. The results demonstrate that the developed predictive model based on Deep Recurrent Neural Network is effective and accurate in predicting the composition of soil and specifications of ground. The preliminary results have been presented in UTC-UTI workshop (Feb. 2018). Phase III has started in Fall 2018. Also, Objective II, Phase I has started in Fall 2018.

PLANNED ACTIVITIES: 1) Developing new methods based on more complex deep learning models that can take into account more data elements to achieve higher accuracy levels; 2) Validating and visualizing the results; 3) Large-scale UTI data collection, exploration, pre-processing for the purpose of adverse event prediction and anomaly detection; 4) Building various predictive models based on combination of supervised and unsupervised machine learning and anomaly detection techniques to predict adverse events such as risks/disasters, defects, and anomalies; 5) Developing and applying the proposed method on other datasets; 6) Publishing and presenting the results in the form of conference and journal papers. The latest results will be presented in TRB 2019 in D.C, and also in UTC-UTI workshop in Oct. As for journal publications, we are under waiting period to get approval from the tunneling project contractor for publishing the results.

PROJECT PERSONNEL: Dr. Mohammad Pourhomayoun (PI), Dr. Mehran Mazari (Co-PI) and Luis Fisher (MS 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 underground transportation infrastructure. Based on this assessment, recommendations will be made for subsequent enhancements. The study is divided into three phases: 1) review and assessment of existing frameworks, 2) engaging stakeholders to prioritize needs, and 3) developing draft specifications for DOTs or draft guidelines to be incorporated in existing tools. The outcomes of this project will help local and national stakeholders take a unified approach to natural disasters, adaptation 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: An assessment was conducted on a sample of underground subway stations in New York, using the Climate Change & Extreme Weather Vulnerability Assessment and Scoring Tool (VAST) proposed by the Federal Highway Administration (FHWA). The assets were assessed under sea level rise and storm surge. The study provided an example for the application of the framework and a means of

evaluating the applicability of the framework to underground transportation assets. This work has been presented and published in the proceedings of the 2018 International Conference on Transportation & Development (ICTD). A literature review has been completed on relevant theoretical papers, sustainability and resilience frameworks, and agency case studies and the evaluation of Envision has been started. An abstract has been submitted for the 2019 International Conference on Sustainable Infrastructure (ICSI) to present the updated results.

MILESTONES ACCOMPLISHMENTS AND DATES: The vulnerability assessment of underground assets using the VAST tool has been published and presented at the 2018 ICTD (July 2018). The literature review was completed in spring 2018. The Envision work has been started. The target date for completing that portion of the study is Jan 7, 2019, at which time the draft paper is due to the ICSI.

PLANNED ACTIVITIES: The current ongoing activity is assessing the applicability of the Envision rating system to underground transportation infrastructure. These tasks fall within phase 1 of the project: review and assessment of existing frameworks. Completion of this task will indicate the end of phase 1.

PROJECT PERSONNEL: Dr. Tonatiuh Rodriguez-Nikl (PI), Dr. Mehran Mazari (co-PI), Edwin Martinez (MSCE Student) and Jose Hernandez (BSCE Student)

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 both during construction and while in use is important for reasons including 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 intertwined aspects to this problem require further study: investigation and development of (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. 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. The convolutional neural network (CNN) is being trained. Preliminary CNN results have achieved a 94.5% accuracy in automated detection of cracks and other blemishes.

MILESTONES ACCOMPLISHMENTS AND DATES: The first prototype was developed and tested in summer 2017. A preliminary assessment of machine learning algorithms was finished in Fall 2017. The second prototype was competed in summer 2018. Training of the CNN is ongoing. Once the CNN and prototype are ready, the system will be deployed to test identification of cracks in field applications.

PLANNED ACTIVITIES: The following activities are currently ongoing: 1) Programming in TensorFlow and Python for Inception-V4 deep CNN network and 2) design and development of an inertial navigation system for inside tunnels and synchronous tagging of the images with precise geo-location information.

PROJECT PERSONNEL: Dr. Fred Daneshgaran (PI), Dr. Marina Mondin (co-PI), Francesco Di Stasio, Politecnico Di Tornio, Turin, Italy (Visiting scholar at CSULA, PhD candidate), Luca Zacheo, Politecnico Di Tornio, Turin, Italy (Visiting scholar at CSULA, MSEE student), Pouya Ebrahimi (MSEE Student).

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: This study includes three phases. Phase I consists of a comprehensive literature review and documenting the state of practice and state of the art related to the properties and application of SCC and fiber-reinforced SCC. The second phase mainly includes designing the fiber-reinforced SCC mix, identification of recycled and sustainable materials for the mix, evaluating the fresh and hardened properties of laboratory specimens and documenting the results. The third phase includes development of models to correlate fresh and hardened propertied of fiber-reinforced SCCs to the mix proportioning and properties of fibers, as well as developing analytical models and prediction algorithms to investigate the performance criteria. The research is in phase II.

MILESTONES ACCOMPLISHMENTS AND DATES: We have identified industry partners to provide the recycled materials and fibers. The preliminary investigations for the development of analytical models and data processing algorithms are also currently in process. A joint webinar with TranSET UTC (at Louisiana State University) was presented in July 2018.

PLANNED ACTIVITIES: The laboratory testing and evaluation, as well as development of database and analytical models, will be continued. Extended testing of fiber-reinforced SCC specimens will be performed. The potential collaborations with DOT and other industry partners are planned.

PROJECT PERSONNEL: Mehran Mazari (PI), Tonatiuh Rodriguez-Nikl (co-PI), Hector Cruz (MS CE student), Jason Ng (BS CE Student).

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 more recently accepted for publication in the Transportation Research Record. 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 in Belfast, Northern Ireland in June 2018. The work will be soon submitted to Fire Safety Journal for review.

MILESTONE ACCOMPLISHMENTS AND DATES: 1) Literature review and database - May/01/2017. 2) Establishment of tunnel prototypes - June/01/2017, 3) Evaluation of prototypes to near field blast effects and conference summary paper – August/01/2017, 4) Presentation at TRB Annual Meeting – January/07/2018, 5) Acceptance of blast paper to Journal of the TRB – March/15/2018, 6) Evaluation of prototypes to radiation and convection from severe fire and summary conference paper – March/26/2018, 7) Presentation at Fire Conference June 2018, 8) Refinement of fire models to account for variation in tunnel geometry (rectangular, horseshoe, round), mesh sensitivity, and fire size – June to Aug 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.

PLANNED ACTIVITIES: 1) Perform validation of tunnels subject to various *blast* demands using computational fluid dynamics. 2) Complete and submit fire assessment paper. 3) Examine effects of blast pressure and thermal demands on false ceiling systems used in tunnels. 4) Identify standard ceiling systems and conduct assessment of propensity for progressive collapse. 5) Develop comprehensive framework for deploying the "intermediate" models for assessment of fire effects and blast in tunnel evaluation. 6) Conduct a case study assessment of resilience of a sample tunnel system based on allowable operation.

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

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

SUMMARY: This research effort was a direct continuation of activities initiated in Year 1 of this award. 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.

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 – September 2018.

PLANNED ACTIVITIES: 1) Initiate numerical modeling of panels. 2) Coordinate with CSM on blast evaluation of panels 3) Develop damage correlation estimation procedure based on thermal test results 4) complete blast sensitivity study to illustrate the influence of substrate on blast damage of liners, 5) validate blast study, 6) develop design methodology and sample liner concepts for enhanced blast and fire resistance.

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

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 34 students (12 PhD, 7 MS and 15 BS) of which 24, 6 and 4 students were engaged in research at CSM, CSULA and Lehigh, respectively. All graduate students are actively working on their thesis and dissertations and are progressing towards the completion of their degrees. Thirteen REU (Research Experiences for Undergraduate) students assisted the graduate students in their research.

b) UTC-UTI students participated and presented papers in several conferences including*:* 1) *52nd US Rock Mechanics/Geomechanics Symposium,* Seattle, WA, June 17–20, 2018*;* 2) *World Tunnels Congress,* Dubai, UAE, April 22-26, 2018*;* 3) *Association of Environmental and Engineering Geologists Annual Meeting,* San Francisco, CA. September 17-21, 2018*;* 4) *10th International Conference on Structures in Fire, Northern Ireland in June 6-8, 2018; and* 4) *Resilience Innovations Summit and Exchange (RISE)*, Denver, CO, October 8-11, 2018.
c) 15 CSM graduate students completed a design project on the LA Regional Connector 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 and design personnel from the project during a May 2-3, 2018 site visit.
d) A CSM PhD student carried out a research internship on the LA Regional Connector project from July 2018. The student is embedded with the cavern excavation team on the project, enabling him to best carry out his PhD research.
e) 21 CSM students attended the North American Tunneling Conference in Washington, D.C. in June 2018. Four CSM students were co-authors on papers and presented at the conference.
f) Approximately 60-80 students each time have participated in UTC-UTI co-sponsored "*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
g) One graduate student participated in project meetings and site visits with CDOT to collect tunnel operational data at the Eisenhower-Johnson Memorial Tunnel (EJMT). Another 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.
h) Ten UTC-UTI students participated and gave presentations during Special Session on University Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course on October 18, 2018 in CSM.
i) A PhD student participated in activities associated with the use of the RAMAX Laboratory in California and assisted with the waterjet cutting tests.
j) A PhD student submitted a 3D geologic modeling animation to the EarthScope visualization challenge by UNAVCO.
k) Cal State LA led a field trip to the regional connector project. Two students attended.
l) Cal State LA organized a field trip to a Precast Tunnel Liner production facility. One faculty and three students attended. Potential collaborations with the industry partner were discussed during the visit.
m) Two Cal State LA undergraduate students were selected for the Transportation Research Board (TRB) Minority Fellows program that highlights the engagement of minority students in research. Both students will be presenting in the TRB Annual Meeting in January 2019.
n) Cal State LA was awarded the administration of Dwight David Eisenhower Transportation Fellowship from Federal Highway Administration. More than 25 undergraduate and graduate students at Cal State LA applied for this year's fellowship.

1.2.3 Outreach Activities

a) UTC-UTI held Session on *Underground Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course* on October 18, 2018. The session had 56 participants (40 from the industry, two from government agencies and 14 from the academe).
b) UTC-UTI and the Tran-SET Center organized a joint webinar with a theme of "*Innovative Concrete Materials for Construction*" with three presentations from UTC-UTI, Tran-SET and Virginia DOT. This free webinar was one hour in length and had 41 participants. Continuing Education Credits and Professional Degree Hours were offered to participants.

c) UTC-UTI sponsored/co-sponsored "*Lunch and Learn*" seminars related to underground transportation infrastructure. The seminars were widely attended by CSM faculty, researchers and students.
d) Dr. Mike Mooney UTC-UTI Associate Director launched a Teach the Professors program for Civil Underground in June 2018. 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 Fall 2019 and Spring 2020.
e) Directed by Dr. Reza Hedayat, CSM delivered an industry short course in May 14-16, 2018 on Grouting and Ground Improvement, including many aspects related to underground transportation infrastructure. A total of 92 industry speakers and participants attended the three-day short course that included a half day field demonstration program.
f) Dr. Hugh Miller began a three-year term on the Board of Directors for the Society for Mining, Metallurgy, and Exploration (SME), which serves and represents the Underground Construction Association (UCA) Division of SME. Dr. Miller has presented at several industry short-courses, invited talks, and conference events.
g) CSM organized two Summer Camps on Tunneling for 42 local 5th to 8th grade students. Each camp featured five days of hands-on activities that introduce the students to underground construction, geotechnical engineering, construction materials and smart infrastructure. In collaboration with CDOT, students also saw tunnels in action through a tour of the Eisenhower-Johnson Memorial Tunnel and the Edgar Experimental Mine in Idaho Springs, CO.
h) CSM and Lehigh University faculty have actively participated as members and supporters of the TRB Standing Committee on Tunnels and Underground Structures, and the AASHTO T20 Committee.
i) A group of middle-school students participated in a tour of concrete laboratory at Cal State LA. Students interacted with the graduate and undergraduate research assistant involved in the concrete project. Students learned about fiber-reinforced self-compacting concrete and its application in underground transportation infrastructure.
j) Cal State LA had a field visit to the Regional Connector Tunneling project in downtown Los Angeles and a group of middle-school students attended this field visit, and interacted with project engineers.
k) The Lehigh University team organized a conference call on August 21, 2018 with AASHTO T20 committee to present the ongoing research and to discuss the committee research needs. Two additional topic areas were identified which will be incorporated into upcoming research plans.

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 potential partners in leveraging UTC-UTI funds to generate additional funding or 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 extensive data and project personnel on the daily operation and maintenance of the Eisenhower-Johnson Memorial Tunnel (EJMT) in connection with UTC-UTI's research on the operational resilience of tunnels.
b) CDOT has provided project personnel and extensive historical data on the geological studies, design and construction of the EJMT as part UTC-UTI's engineering feasibility study of the future extension of EJMT.
c) Data sets and project personnel from two tunneling projects, LA Metro Regional Connector and Seattle Sound Transit, contributed extensively to this project during this time period.
d) Skanska Construction Company provided $9,000 to support of PhD student Haotian Zhang's living expenses in carrying out his field research on the LA project site.

e) Jay Dee Contractors provided in-kind support valued at $87,500 for the Seattle Northlink project analysis.
f) Lane Construction company is providing access to extraordinary instrumented segmental tunnel lining load processes and data.
g) 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.
h) CSM's Earth Mechanics Institute (EMI) has allowed free use of EMI laboratory facilities for the project funded by UTC-UTI. Estimated cost match is $10,000.
i) CSM IET Waterjet Foundation has provided more than $3,500 support for travel.
j) Tongji University, China, has provided extensive data on tunnel construction projects and operation in China including the MuZhaiLing tunnel.
k) An REU (Research Experiences for Undergraduates) site proposal, based on the research being carried out by UTC-UTI, was re-submitted to the National Science Foundation in August 2018. If funded, the aim is to provide support for four undergraduate students each year at CSM, CSULA, and Lehigh to join UTC-UTI research activities during summers.

1.2.5 Faculty and Researcher Accomplishments[i]

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

a) Dr. Reza Hadayat received the $750,000 Early Career Award from the Department of Energy.
b) A paper by Dr. Mehran Mazari, Dr. Mohammad Pourhomayoun and students from CSULA won a Best Paper Award at the 2018 International Conference on Advances in Signal, Image and Video Processing.
c) Dr. Mike Mooney delivered two invited keynote lectures: 1) TBM Deformation Control and Performance Prediction, delivered at the 5th International Symposium on Tunnels and Excavations in Mexico City, Mexico, August 16-18, 2018; and 2) Artificial Intelligence and Physical Model Based Performance Prediction of EPB TBM Tunneling, delivered at the 7th National Symposium on Geotechnical Engineering, Hunan University, Changsha, China, Sept. 21-23, 2018.
d) Dr. Marte Gutierrez, UTC-UTI Director, was member of the Organizing Committee of IS Atlanta 2018 - Geo-Mechanics from Micro to Macro. He co-organized the 2018 US-Norway Summer School on Carbon Capture and Storage (CCS) in the High North held in CSM, and Oslo and Svalbard, Norway. He also gave invited presentations at the University of California San Diego and University of Oslo
e) Dr. Mehran Mazari is on the conference advisory committee for the ASCE's International Conference on Sustainable Infrastructure (ICSI) 2019. He is a member of Scientific Committee and a session moderator at International Conference on Transportation and Development, Pittsburgh, PA, 2018, and the ASCE Transportation and Development Institute Sustainability and Environment Committee.
f) Dr. Andrei Swidinsky received the 2018 Outstanding Geophysics Faculty Member Award by the Order of Omega Greek Honors Society as well as by the CSM undergraduate student body. Dr. Swidinsky is also the organizer of a session on geophysics for underground tunneling during the Society of Exploration Geophysics Annual Meeting in Anaheim Oct 14-19, 2018.
g) Dr. Rennie Kaunda chaired a session at the annual conference of the American Rock Mechanics Association in June 2018

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:

Session on University Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course on October 18, 2018. Presentations are posted in: Zenodo. https://zenodo.org/record/1464772#.W8ctHGgzZ3g

Selected Journal Publications:

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

Hampton, J., Gutierrez, M., Matzar, L., Hu, D. and Frash, L. (2018), Acoustic Emission Characterization of Microcracking in Laboratory Scale Hydraulic Fracturing Tests. *Journal of Rock Mechanics and Geotechnical Engineering,* vol. 10(5), pp. 805-817.

Li, X., Xie, Y., Xu, J. and Gutierrez, M. (2018). A Soft-Rigid Contact Model of MPM For Granular Flow Impact on Retaining Structures, *Computational Particle Mechanics*, vol. 5, no. 2, pp. 1-9

Mori L. and Mooney, M.A. (2018). Characterizing the Influence of Stress on Foam Conditioned Sand for EPB Tunneling, *Tunnelling & Underground Space Technology*, 2018, 71, 454-465.

Prassetyo, S.H. and Gutierrez, M. (2018). High-order ADE scheme For Solving Fluid Diffusion Equations in Non-Uniform Grids and its Application in Coupled Hydro-Mechanical Simulation. *International Journal of Numerical and Analytical Methods in Geomechanics*, 42(16), pp. 1976-2000,

Shirole, D., Walton, G., Ostrovsky, I., Masoumi, H. and Hedayat, A. (2018). Non-linear Ultrasonic Monitoring of Damage Progression in Disparate Rocks. *International Journal of Rock Mechanics and Mining Sciences*, 111, pp. 33-44.

Wu, Y., Mooney, M.A. and Cha, M. (2018). An Experimental Examination of Foam Stability under Pressure for EPB TBM Tunneling, *Tunnels & Underground Space Technology*, 77, pp. 80-93.

Selected Conference Papers and Presentations:

Cruz, H., Ng, J., Ojeda, F. and Mazari, M. (2018). Effect of Fiber-Reinforcement on Mechanical Properties of Self-Consolidating Concrete for Transportation Infrastructure Applications. *International Conference on Transportation and Development*, ASCE, Pittsburgh, PA.

Epel, T., Mooney, M., Gutierrez, M., Braun, K., DiPonio, M. and Long N. (2018). Ground-Liner Interaction during Seattle Northlink Cross-Passage Construction. *North American Tunneling Conference*, Washington D.C., June 24-27, 2018.

Hedayat, A., Weems, J., and Roshan, H. (2018). Stress and Deformation Analysis of Circular Tunnels with Consideration of Blast-Induced Damage and Gravity. *52nd US Rock Mechanics Symposium*, Seattle, June 17-20.

Krajnovich, A., Zhou, W. and Gutierrez, M. (2018). A Bayesian Approach to Adaptive and Predictive 3-D Geologic Modeling for Tunneling Projects. Association of Environmental and Engineering Geologists Annual Meeting, San Francisco, CA. September 17-21, 2018.

Martinez, E., Hernandez, J., Rodriguez-Nikl, T. and Mazari, M. (2018). Resilience of Underground Transportation Infrastructure in Coastal Regions: A Case Study. *International Conference on Transportation and Development*, ASCE, Pittsburgh, PA.

Mifkovic, M., Swidinsky, A. and Mooney, M. (2018). Imaging Ahead of Tunnel Boring Machines with DC Resistivity: A Laboratory Study. *SEG Conference*, Anaheim, USA, October 14-19, 2018.

Mooney, M., Zhang, X., Wu, H. and Zhou, X. (2018). EPB TBM Performance Prediction. *North American Tunneling Conference*, Washington D.C., June 24-27, 2018.

Packman, S., Lopez, S., Mazari, M. (2018) "Evaluating the Resilience of Transportation Infrastructures to Extreme Weather Events using Soil-Moisture Active Passive Satellite Data*", International Conference on Transportation and Development*, ASCE, Pittsburgh, PA.

Prassetyo, S.H. and Gutierrez, M. (2018). Designing Tunnel Support Systems Based on Ground Reaction Curve and Equilibrium Strain Approach. *World Tunnel Congress*, Dubai, UAE. April 21-26, 2018

Root, K., Guo, Q., Quiel, S. and Naito, C. (2018). Calculating Fire-Induced Heat Flux Contours on Concrete Tunnel Liners to Evaluate Structural Consequences," *10th International Conference on Structures in Fire*, Belfast, Ireland, June 2018.

Wnuk, K., Zhou, W., Walton, G. (2018). InSAR Analysis of Surface Subsidence above a Headrace Tunnel in the Sri Lankan Highlands. Association of Environmental and Engineering Geologists Annual Meeting. San Francisco, CA. September 21, 2018.

Wu, Y., Nazem, A. and Mooney M. (2018). The EPB Chamber Air Bubble: What Causes It? *North American Tunneling Conference*, Washington D.C., June 24-27, 2018.

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, meeting presentation slides, publications and technical reports from UTC-UTI can be downloaded from this site.

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.

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, China (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 (Seatle, WA and Lakewood, CO), 7) LA Metro (Los Angeles, CA, 8) Skanska Construction Co. (Los Angeles, CA); 9) Seattle Sound Transit (Seattle, WA); 10) L-7 Services (Golden, CO); 11) Traylor Brothers Inc. (Los Angeles, CA); 12) WSP (Los Angeles, CA); 13) University of British Columbia (Vancouver, Canada), and 14) Lane Corporation (Washington, D.C.).
c) Representatives from the following organizations have *given presentations in the UTC-UTI co-sponsored seminar series*: 1) Skanska USA (Los Angeles, CA); and 2) Kiewit (Omaha, NE).

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. UTC-UTI has also established a collaboration with the Tran-SET Center on holding free joint webinars, and the University of British Columbia on software use and development.

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 therefore 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. It is envisioned that 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 16 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 webpage.

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 three ways: 1) working with various components of the underground transportation industry for direct technology transfer, e.g., through industry-funded, co-funded or cost-matched research; 2) sharing of innovations via continuing education, seminars and workshops; and 3) dissemination through publications of research in journals and conference proceedings, reports, and design manuals, and through our archiving and dissemination website at Zenodo. Activities which illustrates UTC-UTI's strong commitment to technology transfer include: 1) Session on Underground Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course, 2) Joint webinar with a theme of "Innovative Concrete Materials for Construction" with three presentations from UTC-UTI, Tran-SET and Virginia DOT, 3) Teach the Professors program for Civil Underground in June 2018, and 4) Industry short course on Grouting and Ground Improvement.

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.

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