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

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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 15 research projects (nine at CSM, four at CSULA and two at Lehigh). One CSM project was completed. Highlights of these projects are given below.

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

TITLE OF THE PROJECT: Data-driven risk mitigation of tunnel 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. 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) examine the use of TBM-ground modeling extracted stiffness to reduce sequential excavation method deformation.

PROJECT STATUS: (Obj. 1) The evaluation of liner loads monitored during Seattle Northlink tunnel construction has been completed. The assessment of liner design practice and comparison to measured loads is underway. (Obj. 2) The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is nearing completion and 3D finite element modeling is underway. (Obj. 3) Analysis of LA metro TBM and ground monitoring data through the Regional Connector crossover cavern area is underway.

MILESTONES ACCOMPLISHMENTS AND DATES: 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.

PLANNED ACTIVITIES: Continued analysis of field data and shifting effort towards 3D finite element modeling for objectives 2 and 3.

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: This project started in August 2017. The research team is developing a framework for data collection for critical roadway tunnels in the U.S. in order to gather functionality loss data from tunnel daily operation.

MILESTONES ACCOMPLISHMENTS AND DATES: The project team has held multiple meetings with CDOT to discuss collaboration using Eisenhower-Johnson Mountain Tunnel on I-70 as an example. The project team has acquired some historical operation record data from the tunnel to test the newly developed data framework.

PLANNED ACTIVITIES: The research team plan to collaborate with an industry partner to enable collection of critical tunnel operation data through a computer-based platform (traditionally most of the CDOT critical tunnel operation data was collected manually on paper). The research team also plan to conduct a survey study with DOT tunnel owners to identify the current status of operation data collection for tunnels. At the same time, the researchers will use critical tunnels in Colorado to conduct case studies on operation data analysis, as well as developing probabilistic framework for tunnel functionality loss analysis.

PROJECT PERSONNEL: Dr. Shiling Pei, Dr. Marte Gutierrez and PhD student Sandeep Khetwal.

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

SUMMARY: Uncertainties in rock mass characterization and classification have been significantly important in the field underground construction. The proposed Markovian rock mass quality Q-based prediction model, which is the combination of Markovian prediction approach and the probabilistic evaluation of rock mass quality Q-system, is capable of characterizing the uncertainty in the prediction of rock mass quality before construction. Based on the transition intensity matrixes (transition probability and transition intensity coefficient) of Q-parameter states, which can be estimated from the general geological information, and the probabilistic Q-log exploration results, as can be obtained from local geological information (e.g. boreholes), the probabilistic distribution profiles for each state of Q-parameters can be derived along the tunnel axis using the Markovian prediction technique. The probability distribution of overall Q-value can be thereby obtained along the tunnel axis by combining the distributions of Q-parameters using Monte Carlo simulations. Given the distribution of Q-value, the relative percentage of Q-based rock classes can also be easily obtained. The combination of probabilistic support pressure and the distribution of Q-based support class can provide decision support for selection of appropriate support scheme for tunneling.

PROJECT STATUS: This project has started in January 2017 and has almost completed the first objective. The following tasks are in progress: 1) Major literature review completed. 2) Three data sets were acquired from some tunnels. 3) The Markov chain approach has been developed and will be used to analyze a Hong-Kong tunneling project.

MILESTONES ACCOMPLISHMENTS AND DATES: This project has started in January 2017 and has almost completed the first objective. A probabilistic Q-based prediction model to characterize the uncertainties in the Q-rock mass classification system was completed on March 2018.

PLANNED ACTIVITIES: Development of the updating algorithm and the reliability method will continue, including: 1) Validation of the predicted probabilistic Q in the unexcavated tunnel sections against actual Q collected from tunnel mapping during construction. 2) Development of updating schemes using Bayesian updating or others technique to use newly available Q-data during construction to update the Q prediction model. 3) Investigation of the predicted probabilistic Q with instrumented or monitored data (e.g., deformation) collected during construction using reliability-based method with deformation-based limit state function.

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

TITLE OF THE PROJECT: New excavation technologies for underground construction.

SUMMARY: The costs of tunneling projects have increased over time, especially during the excavation of difficult ground. Further, excavation challenges are exacerbated as the depth of the tunnel increases. As a result, researchers have considered alternate excavation technologies such as application of microwaves for pre-conditioning and weakening of rock to reduce the cost of mechanical excavation in hard rock. Laboratory experiments such as large scale linear cutting of bulk rock blocks can help evaluate the energy requirements during rock excavation. A linear cutting machine (LCM) is a device that provides a direct measurement of rock cuttability for different simulated field conditions. The LCM has the capability to measure the forces acting on a single disc cutter while making a cut at the rock surface. Using various sensors mounted on the LCM and because of the large scale of the tests, a direct assessment of machine performance can be made in terms of specific energy computations. Specific energy is the amount of energy required to excavate a unit volume of rock. The objectives of this project are: (1) to measure energy requirements for hard rock which has been weakened by microwave irradiation by conducting laboratory large scale linear test experiments (2) To develop a knowledge base that facilitates the analysis of the impact of rock strength on the test results and provides the opportunity to extrapolate the results of the rock cutting tests to similar rock types.

PROJECT STATUS: Project planning and design has been completed, and is now in the execution stage. Preliminary large-scale linear cutting tests on microwave irradiated granodiorite rock blocks have been completed. Consequentially, Objective 1 is on schedule towards completion. Additional research tasks and resources are required to complete Objective 2, and to support technical presentations and publications.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) The large-scale LCM tests resulted in a database with specific energy values comparing pre-conditioned versus unconditioned granodiorite rock blocks. (2) One technical report. (3) Two technical presentations during 2018. (4) One MS student mentored, who graduated in Fall 2017

PLANNED ACTIVITIES: Anticipated research plan moving forward will be to improve the statistical validity of experimental results obtained to date. In addition, rock mechanical tests including compressive strength tests (UCS plus elastic properties), punch penetration, and Cerchar Abrasivity Index (CAI) tests will be conducted.

PROJECT PERSONNEL: Dr. Rennie Kaunda and MS Student Shrey Arora.

TITLE OF THE PROJECT: Physical model 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 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.

PLANNED ACTIVITIES: Research plan for this year onward will be to design the mix for the rock-like materials to be tested in the true-triaxial apparatus. The major task will be the design and construction of the tunnel boring machine for use with the true-triaxial apparatus and the required instrumentation inside the rock.

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: Tunneling has become an increasingly choice of providing infrastructure to transportation. Transportation tunnels are often constructed close to the surface, sometime in densely populated urban areas, increasing the likelihood of excavation-induced ground subsidence, and potential damages to infrastructures immediately above the ground. It is therefore necessary to quantify tunneling-induced ground surface deformation with time. 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.

At this stage of the project, we are in the process of developing Persistent Scatterer (PS) and Small Baselines Subset (SBAS) InSAR time-series techniques. A dataset of ascending and descending Synthetic Aperture Radar (SAR) satellite images with high temporal resolution were acquired by Sentinel-1 (the first of the Copernicus Program satellite constellation conducted by the European Space Agency), and were processed to produce Interferometric SAR (InSAR). 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 rural area with more advanced InSAR techniques, such as SBAS, PS, and TRAIN, where we have successfully identified widespread subsidence in an area directly above tunnel excavation where significant water ingress was reported.

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 2017.

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. We are also testing the feasibility of using the Toolbox for Reducing Atmospheric InSAR Noise (TRAIN), a relatively new technique developed to identify atmospheric signals that are correlated in space but not in time. These results will be submitted for publication within the year.

PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Gabe Walton 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. Quantifying the uncertainty associated with predictions of the expected geology is essential to ensuring the effective use of the 3D geologic model in informing the tunnel design. 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 assess the quality of the current geologic model, and to update the model to account for previously unknown structures. Bayesian statistics provide a convenient framework for quantifying prediction uncertainty from a variety of sources (e.g., hard data, interpretations) and for updating the predictive model in light of new observations. 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. (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 and has since completed the literature review stage. Currently, a detailed project proposal draft is being written which outlines the methodology for achieving each research objective. Suitable software and data sources are also being finalized at this time.

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 2017. Additionally, a revised abstract has been submitted to the 2018 AEG Annual Meeting as of April 1st, 2018.

PLANNED ACTIVITIES: (1) Processing of geologic data acquired from a modern tunneling project. (2) Preparation for an oral presentation under the Tunneling Symposium at the 2018 AEG Annual Meeting. (3) Bayesian model formulation for prediction of geologic structures along a tunnel alignment.

PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez and Ph.D. 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 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 a new MS graduate research project and most laboratory experiments have been completed as of March 2018.

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-Mar 2018).

PLANNED ACTIVITIES: Research work of the upcoming year will consist of numerical simulations to cross-validate and better understand experimental laboratory results, followed by the planning of a field experiment on a full scale TBM. Long term activities will consist of carrying out these 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 MS 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 conventional shotcrete removal and repair, this research seeks to develop a unique system that utilizes waterjet technology as the primary excavation tool. Building upon the success of previous CSM research activities in underground rock scaling and scarification, empiric evidence 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 compare and contrast the unintended damage caused to the surrounding structural liner and rock substrate by both conventional impact hammers and waterjet excavation methods during empiric testing. This analysis will involve physical testing on instrumented shotcrete panels designed to quantify fracture propagation, substrate delamination, and stress distribution. The intent of this research is to facilitate a better understanding of the dynamic excavation processes associated with liner repair in hopes of developing a future prototype system applicable for field testing.

PROJECT STATUS: The research project started in May 2017. To date, the project phases associated with engineering, design, and equipment fabrication and assembly have been completed. Similarly, the laboratory instrumentation and mechanical/waterjet set-ups have been completed and the construction and instrumentation of the test panels are also nearing completion. Data collection is currently underway, where data analysis will follow.

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 nearly completed (March 2018). (4) Empiric testing and data analysis are scheduled to be completed by mid-July 2018.

PLANNED ACTIVITIES: Research plan for the next three months includes the completion of the laboratory testing and data analysis, and the subsequent publication of the results and final report.

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

Research at California State University Los Angeles

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. At the outset of the project, the two frameworks of greatest interest are Envision (Institute for Sustainable Infrastructure) and FHWA's Climate Change & Extreme Weather Vulnerability Assessment Framework. 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 tools such as Envision and FHWA framework. 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).

PROJECT STATUS: A preliminary assessment has been 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 goals of the preliminary assessment were to provide an example for the application of the framework and to evaluate the applicability of the framework to underground transportation assets. This work has been accepted for peer-reviewed publication and poster presentation at the 2018 International Conference on Transportation & Development. A literature review is currently being conducted on relevant theoretical papers, sustainability and resilience frameworks, and agency case studies. A progress report will be finished in May as part of an undergraduate independent study conducted by an undergraduate research assistant.

MILESTONES ACCOMPLISHMENTS AND DATES: The vulnerability assessment of underground assets using the VAST tool has been accepted for publication and poster presentation at the 2018 International Conference on Transportation & Development (acceptance March 2018, presentation July 2018). We are continuing phase 1 activities and plan to present at the 2019 TRB Annual Meeting.

PLANNED ACTIVITIES: The immediate next steps are to continue the literature review and to assess the applicability of the Envision rating system to underground transportation infrastructure. A summary of the work to date will be proposed for presentation at the 2019 TRB Annual Meeting. These tasks fall within phase 1 of the project: review and assessment of existing frameworks. Several additional frameworks will be assessed before moving on to phases 2 and 3.

PROJECT PERSONNEL: Tonatiuh Rodriguez-Nikl (PI), Mehran Mazari (co-PI), Edwin Martinez (MS CE Student), Jose Hernandez (BS CE Student)

TITLE OF THE PROJECT: The 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. A main objective is to develop advanced data mining and novel machine-learning-based methods for predicting or detecting the specifications of ground and geological conditions based on the data collected before or during the TBM operations. The current method of estimating soil conditions (e.g. Kriging method) is based on statistical analysis that is extrapolated from soil samples. These models do not take into account the vast amount of information collected from TBM in real time. The aim of this project is to use recent advancements in machine learning to build a data-driven predictive model to predict soil conditions and composition. This research project includes 3 main phases, Phase I: large-scale UTI data collection, exploration, and data processing; phase II: knowledge extraction, data analytics, predictive analytics based on advanced machine learning; phase III: refine the prediction methods and accuracy, data visualizations and data storage.

PROJECT STATUS: This project started in June 2017. We have completed phase I of the project based on a big dataset received from the Seattle Northlink project and are progressing on phase II. A new efficient prediction technique has been developed based on an advanced deep learning method called Recurrent Neural Network (RNN). The preliminary results demonstrate that the proposed method is very effective and accurate in predicting the composition of soil and specifications of ground.

MILESTONES ACCOMPLISHMENTS AND DATES: Completion of Phase I: March 2018.

PLANNED ACTIVITIES: (1) Develop new techniques to refine and improve the accuracy of the proposed predictive models, (2) develop new machine learning algorithms for comparison with the current proposed method, (3) publishing and presenting the results in the form of conference and journal papers (as soon as we get approval from contractor company), (4) developing visualization methods, and (5) developing and applying the proposed method on other datasets, e.g., adverse events and disaster/risk management.

PROJECT PERSONNEL: Mohammad Pourhomayoun (PI), Mehran Mazari (co-PI), Luis Fisher (MS CS 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 (1) 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); (2) tools and techniques to acquire the data in an efficient and automated manner and communicate the information to proper processing center; (3) suitable techniques for post processing of acquired data to generate an intermediate observation space on which detection algorithms may be applied; (4) 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 prototype has been deployed and tested. Based on the performance of this prototype, we are currently developing prototype-II data acquisition system using commercial, off the shelf equipment. We expect a much higher resolution imagery from our prototype-II that uses DLSR camera with high intensity LED arrays and synchronized flash lights as two alternative lighting options. Our next goal is to design and build the vehicle mounted platform that will house the prototype-II.

MILESTONES ACCOMPLISHMENTS AND DATES: The first prototype was developed and tested in summer 2018. A preliminary assessment of machine learning algorithms was finished in Fall 2018. These results have guided the development of the subsequent prototype.

PLANNED ACTIVITIES: The following activities are currently ongoing: (1) Programming in TensorFlow and Python for Inception-V4 deep CNN network; (2) Design and development of prototype-II; and (3) design and development of an inertial navigation system for inside tunnels and synchronous tagging of the images with precise geo-location information.

PROJECT PERSONNEL: Fred Daneshgaran (PI), Marina Mondin (co-PI), Francesco Di Stasio, Politecnico Di Tornio, Turin, Italy (Visiting scholar at CSULA, Ph.D. candidate), Luca Zacheo, Politecnico Di Tornio, Turin, Italy (Visiting scholar at CSULA, MS EE student), Pouya Ebrahimi (MS EE 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 initial stages of phase II.

MILESTONES ACCOMPLISHMENTS AND DATES: The research is in initial stages of phase II. Preliminary mixes were designed and constructed in the lab and the mix proportioning for the fiber-reinforced SCC is undergoing. 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.

PLANNED ACTIVITIES: Research plan for this year includes designing the new SCC and fiber-reinforced SCC mixes and evaluate the fresh and hardened properties in the laboratory. Different types of recycled materials and fibers will be identified and provided in collaboration with industry partners.

PROJECT PERSONNEL: Dr. Mehran Mazari (PI), Dr. 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 making efforts to develop a new framework for evaluating the vulnerability of tunnel infrastructure to blast and fire hazards. Blast and fire will be evaluated both 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 will be used to prioritize and tailor mitigation strategies, systems, and placement to maximize risk reduction with available resources. The project team has previously developed several fast running analysis techniques for analyzing the effects of blast and fire on large structural systems – these methodologies will be leveraged to evaluate the effects of blast and fire on large tunnels or inventories of tunnels via large batches of simulations using randomly selected inputs. This effort is computationally focused, and funds dedicated to this project will be 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, chosen 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 Journal of the Transportation Research Board. 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 Fire Dynamics Simulator (FDS) is utilized for validation of the intermediate approach. FDS models are compared against existing experimental work by others to confirm acceptability of the process in the tunnel environment. This work has been accepted for presentation at the 2018 Structures in Fire Conference in Belfast, Northern Ireland in June 2018. The result will be soon submitted to the 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.

PLANNED ACTIVITIES: (1) Refine "intermediate" models for spatial and temporal distributions of hazard demands on the tunnel structure. (2) Perform parametric evaluation of tunnels subject to varying *thermal* demands, including damage modes and structural consequences. (3) Perform parametric evaluation of tunnels subject to various *blast* demands, including damage modes and structural consequences. (4) Develop frameworks for deploying the "intermediate" models in practice and examine implementation with local DOTs.

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

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

SUMMARY: This project will develop new structural design strategies for mitigation of blast and fire hazards in tunnels. A novel precast segmental liner will be designed for efficient installation and replacement. The scope of demands to be considered will be 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 developed based on first principles and current state of the art will be numerically evaluated under the range of load expected. Numerical models will be verified using case study data. The designs will be refined using parametric evaluations. Preliminary experimental investigation of the prototype liner will be conducted to verify resistance to close in blast and fire exposure. Testing will be conducted at facilities available at Lehigh University and Colorado School of Mines. Based on preliminary results, designs may be altered to enhance performance, and final verifications will be experimentally conducted. Cost and construction efficiencies will be incorporated during the development phases

PROJECT STATUS: An extensive numerical evaluation of concrete lining under blast loading has been performed. LS-DYNA is employed to develop a further understanding of the failure mechanisms present in such events. Parameters effecting damage for a given charge size are numerically evaluated: backfill material, liner thickness and strength. Correlations for damage and backfill material are currently in development. A journal publication summarizing this effort will be submitted for review in the next quarter to the international Journal of Impact Engineering.

The behavior of concrete lining under fire conditions is being investigated experimentally. An experimental program has been developed to investigate the effect of pertinent parameters on the propensity of thermal spalling; parameters include rebar density, applied axial stress, and magnitude of thermal exposure. Fabrication of the experimental test set up has been completed and will soon be calibrated in preparation for testing. Custom formwork has been fabricated in-house to cast the concrete test specimens at the Lehigh facilities. Casting of the test specimens and subsequent testing is scheduled for spring 2018. Test data will be coupled with the computational models developed to create a total damage mapping tool, capable of conservatively predicting tunnel liner damage for a given fire event.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Literature review and database- May/01/2017. (2) Fire test matrix - June/01/2017. (3) Initiate numerical modeling of thermal effects - June/15/2017. (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.

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 (expected graduation September 1, 2018), Ph.D. student Qi Guo, Ph.D. student Aerik Carlton (expected start date July 1, 2018), Faculty Dr. Clay Naito and Dr. Spencer Quiel.

1.2.2 Student Activities

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

a) A total of 13 students (10 Ph.D., three MS and one BS), seven students (one visiting Ph.D., five MS and one BS), three students (two Ph.D. and one MS) 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. One MS student graduated in 2017.
b) UTC-UTI students participated and presented papers in several conferences including: 1) The *6th International Symposium on Geotechnical Safety and Risk* in Denver, CO, June 2017; 2) *Rapid Excavation and Tunneling Conference* in San Diego, CA, in June 2017; 3) The *TRB Annual Meeting* in Washington DC in January, 2018; 4) *Association of Environmental and Engineering Geologists Annual Meeting* in Colorado Springs, CO, in September 2017; 5) *The Society for Mining, Metallurgy, and Exploration (SME) Annual Meeting* in Minneapolis, MN, in February 2018; 6) *Waterjet Technology Associate (WJTA- IMCA) Annual Conference* in New Orleans, LA, in October 2017; and 7) *The CSULA 26th Annual Student Symposium on Research, Scholarship and Creative Activities*.
c) All 23 UTC-UTI students participated and gave presentations during the *First UTC-UTI Workshop* held at CSM on February 18, 2018.
d) 15 CSM graduate students are completing a design project on the LA Regional Connector transit tunnel project. They will design the liner, assess building deformation and develop TBM face pressure calculations along the alignment. The students will present their findings to LA Regional Connector project personnel during a May 2-3, 2018 site visit.
e) Approximately 60-80 students each time have participated in UTC-UTI co-sponsored "*Lunch and Learn*" Seminars in the Fall 2017 (eight lectures) and Spring 2018 semesters (11 lectures). 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.
f) One graduate student participated in project meetings and site visits with CDOT to collect tunnel operational data at the Eisenhower- Johnson Memorial Tunnel.

1.2.3 Outreach activities

a) UTC-UTI held of its *First Symposium on Underground Transportation Infrastructure* on September 21 and 22, 2017 at Colorado School of Mines. The theme of the First UTC-UTI Symposium was on the "*Challenges and Opportunities for Underground Transportation Infrastructure in the US*." The goal of the symposium was to identify research needs and opportunities. The symposium had 47 participants (24 from the industry, three from government agencies and 20 from the academe), and highlighted presentations from leading experts in the field, and work being carried out by UTC-UTI. Breakout sessions to discuss research needs in UTIs and to guide future research agenda of UTC-UTI were held at the end of the Symposium.
b) UTC-UTI and the Tran-SET Center have stablished a working collaboration to offer free joint webinars. The first joint webinar will be offered in July 2018 with a theme of "*Innovative Concrete Materials for Construction*" and will include three presentations from UTC-UTI, Tran-SET and Virginia DOT. This free webinar will be one hour in length and with up to 200 anticipated participants.
c) The *First UTC-UTI Workshop* was held at CSM on February 18, 2018. Faculty, researchers and students from CSM, CSULA and Lehigh as well from four universities in China participated in the Workshop.
d) 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.

e) Dr. Priscilla Nelson of CSM was active in student recruiting from Colorado Community Colleges into Mines programs, in "*Girls Lead the Way*" and in the "*Women in STEM Day of the Denver Public Schools*." She participated in Workshops on Connecting Women Faculty in Geotechnical Engineering—Thriving in a Networked World, funded by NSF, on April 10 and 11, 2017 and March 6, 2018.
f) Dr. Mooney of CSM developed a "*Teach the Professors*" Program for Civil Underground. Ten professors from Civil Engineering programs around the US will: 1) attend the North American Tunneling conference in Washington DC in June 2018; 2) assist in underground-driven civil engineering curriculum, and (3) implement the curriculum in their classrooms during Fall 2019 and Spring 2020
g) Dr. Wendy Zhou of CSM assisted the AEG Tunneling Focus Group in developing information for their webpage.
h) Dr. Hugh Miller of CSM 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 is also the 2019 President-Elect for SME.
i) Lehigh University MS student Kyle Root presented his ongoing research to Lehigh University graduate students in Structural Engineering as part of the Fritz Engineering Research Society Seminar Series at the ATLSS Research Center. He also provided an overview of the capabilities of Grasshopper and Rhino, two software tools used as part of the research effort at Lehigh, to Lehigh's Department of Art and Architecture.

1.2.4 Leveraging UTC-UTI funds

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) A proposal was submitted to CDOT for the engineering feasibility study of the future extension/expansion of the Eisenhower-Johnson Mountain Tunnel (EJMT).
b) An REU (Research Experiences for Undergraduates) Site proposal, based on research being carried out by UTC-UTI, was submitted to the National Science Foundation in August 2017. The aim is to provide support for four to five undergraduate students per year each at CSM, CSULA and Lehigh to join UTC-UTI research activities during summers. Unfortunately, the proposal was declined. It will be re-submitted for the next competition.
c) Extensive data sets and project personnel from two tunneling projects, the LA Metro Regional Connector and the Seattle Sound Transit, were contributed to UTC-UTI.
d) RAMAX LLC will provide 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
e) IET Waterjet Foundation is providing $3,500 support for travel.
f) MapTek contributed licenses for the I-Tech MVS/Earth Volumetric Studio software suite to CSM. This software suite is currently being used for several UTC-UTI projects.
g) Tongji University, China, has committed to provide extensive data on tunnel construction projects and tunnel operation in China.
h) CDOT has provided data on daily operations of and access to the Eisenhower-Johnson Mountain Tunnel (EJMT).
i) Equipment required for thermal testing was provided by Lehigh University via faculty startup fund for Dr. Spencer Quiel.

1.2.5 Faculty and researcher accomplishments

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

a) Dr. Marte Gutierrez, UTC-UTI Director, was Keynote Lecturer at the International Conference on Plasticity, Damage, and Fracture. He was a member of the Scientific Advisory Committee of the SUCCESS Center (Subsurface CO_2 Storage - Critical Elements and Superior Strategy), a $25 million research center in Norway. He co-organized the US-Norway Summer School on Carbon Capture and Storage (CCS) in the High North held in Oslo and Svalbard, Norway. In addition to serving in the Editorial Board of four international journals, he became an Editorial Board member of the Journal of Rock Mechanics and Geotechnical Engineering.

b) Dr. Mike Mooney, UTC-UTI Associate Director, delivered an invited lecture on pressure balance TBM tunneling at the May 5 2017 Chicago Geotechnical Lecture Series, and two keynote lectures in November 2017: (i) TBM Deformation Control in Urban Environments, delivered at the 1st international conference on smart underground space in Shanghai Nov 23-25, 2017; and (ii) Soil Conditioning under Pressure in Earth Pressure Balance Tunnel Boring Machines, delivered at TBM DiGs in Wuhan, China, Nov 20-22, 2017.

c) Dr. Priscilla Nelson, UTC-UTI Associate Director for Education, Workforce Development and Diversity received the *2018 UCA Outstanding Educator Award*. She was appointed: (i) to the Editorial Board of Urban Transportation and Construction, Universe Scientific Publishing Pte. Ltd., Singapore; (ii) as member of the Board of Directors of ACUUS (Associated Research Centers for the Urban Underground Space); and (iii) as member of the Scientific Committee of the 2017 World Tunnelling Conference of the International Tunnelling Association, Istanbul, Turkey.

d) Dr. Hugh Miller of CSM will be receiving the prestigious *Medal of Merit Award by the Mining Hall of Fame, Mining Foundation of the Southwest* for his contributions to Mining Education.

e) Dr. Andrei Swidinsky of CSM was made a Member of the *Newmont Academic Associates Program* by Newmont Mining Corporation. He also received the 2017 Outstanding Geophysics faculty award and gave a keynote speech at the 13th China International Geo-Electromagnetic Workshop in Wuhan, China.

f) Dr. Tonatiuh Rodriguez-Nikl of CSULA became a member of the Sustainability Council of the Los Angeles County Metropolitan Transportation Authority (LA Metro).

g) Dr. Reza Hedayat of CSM was in the organizing committee for the 52nd U.S. Rock Mechanics Symposium and served as the track lead for the Civil Infrastructure track of the symposium. Dr. Hedayat gave a webinar as part of the Web conference on Rock Mechanics hosted by ASCE-Geo-Institute in August 2017.

h) Dr. Rennie Kaunda of CSM, attended the Working Group 2 of the World Tunneling Congress in Norway in June 2017, helped organize and chair two sessions at an international mining conference in Africa in July 2017, and chaired a session at the annual conference of the Society of Mining Metallurgy and Exploration in February 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:

Inaugural Symposium of the University Transportation Center for Underground Transportation Infrastructure (UTC-UTI). Zenodo. http://doi.org/10.5281/zenodo.1011102

First Workshop of the University Transportation Center for Underground Transportation Infrastructure (UTC-UTI). Zenodo. http://doi.org/10.5281/zenodo.1226376

Book Chapter:

Rodriguez-Nikl, T. (2017). "Fiber Reinforce Polymers," in Structural Materials and Global Climate, M.D. Webster (ed.), ASCE, Reston VA.

Journal Publications:

Bai, F., Guo, Q., Root, K., Naito, C., Quiel, S. (2018). Blast vulnerability assessment of road tunnels with reinforced concrete liners. *TRB Transportation Research Record, Journal of the Transportation Research Board*, Manuscript Number: 18-05880.

Burkhardt, M., Kim, E. and Nelson, P. (2018). EMI database analysis focusing on relationship between density and mechanical properties of sedimentary rocks. *Geomechanics and Engineering*. 14(15).

Gheibi, A. and Hedayat, A. Ultrasonic Investigation of granular materials subjected to compression and crushing. *Ultrasonics Journal*, 87, 112-125.

Hedayat, A., Haeri, H., Hinton, J., Masoumi, H. and Spagnoli, G. (2018). Geophysical signatures of shear induced damage and frictional processes on rock joint. *Journal of Geophysical Research*. 123 (2), 1143-11605.

Kim, E., Garcia A. and Changani, A. (2018). Fragmentation and energy absorption characteristics of Red, Berea and Buff sandstones based on different loading rates and water contents. *Geomechanics and Engineering*. 4(2).

Mori L. and Mooney M.A. (2018). Characterizing the influence of stress on foam conditioned sand for EPB tunneling, *Tunnelling and Underground Space Technology*, 71, 454-465.

Mori, L., Alavi, E. and Mooney, M.A. (2017). Apparent density evaluation methods to assess the effectiveness of soil conditioning, *Tunnels and Underground Space Technology*, 67, 175-186.

Prassetyo, S.H. and Gutierrez, M. (2018). Axisymmetric ADE scheme for efficient coupled simulation of hydro−mechanical interaction in geotechnical engineering−application to circular footing and deep tunnel in saturated ground, *Journal of Rock Mechanics and Geotechnical Engineering*, 10, 259-279.

Prassetyo, S.H. and Gutierrez, M. (2018). Effect of transient coupled hydro-mechanical response on the longitudinal displacement profile of deep tunnels in saturated ground. *Tunnelling and Underground Space Technology*, 75, 11-20.

Prassetyo, S.H., Gutierrez, M. and Barton, N. (2017). Nonlinear shear behavior of rock joints using a linearized implementation of the Barton-Bandis Model, *Journal of Rock Mechanics and Geotechnical Engineering,* 9, 671-682.

Sarfarazi, V., Haeri, H., Shemirani, A., Hedayat, A., and Hosseini, S. (2017). Investigation of ratio of TBM disc spacing to penetration depth in rocks with different tensile strengths using PFC2D. *Computers and Concrete*, 20(4), 429-437.

Conference Papers and Presentations:

Bai, F., Guo, Q., Root, K., Naito, C., Quiel, S. (2018). Blast vulnerability assessment of road tunnels with reinforced concrete liners, *TRB 97th Annual Meeting*, Presentation Session 812.

Charrier, E., Miller, H. & Steele, J. (2018). Efforts to characterize and mitigate hot work accidents in mining and mineral processing, *2018 SME Annual Meeting, Coal & Energy Division, Mine Safety II*, Minneapolis, MN, Feb. 28, 2018

Epel T, Mooney M, Gutierrez M, Braun K, DiPonio M and Long N. (2018). A comparison of estimated and measured precast segment liner loads developed during construction of twin EPB TBM Tunnels in Seattle. *Proc. World Tunnels Congress*, Dubai, Apr 22-26, 2018.

Epel, T, Mooney MA, Gutierrez M, Braun K, DiPonio M and Long N. (2018). Ground-liner interaction during Seattle Northlink cross-passage construction. *Proc. North American Tunneling Conference*, Washington D.C., June 24-27, 2018.

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.

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

Mooney, MA., Tilton, N., Parikh, D. and Wu, Y. (2018). EPB TBM foam generation. *Proc. Rapid Excavation and Tunneling*, San Diego, CA. June 4-7, 2017, 13 pp.

Nelson, P. (2017). Geologic risk and underground construction, Invited keynote presentation to the ASCE Colorado Section, January 19, 2017.

Prassetyo, S.H. and Gutierrez, M. (2017). Efficient sequential coupling technique for the simulation of hydro-mechanical interaction in rock engineering, *Proc. 51th US Rock Mechanics / Geomechanics Symposium*, Houston, Texas, June 25-28, 2017.

Prassetyo, S.H. and Gutierrez, M. (2017). Explicit high-order ADE solutions for fluid flow in the coupled Biot equations, *Proc. 6th Biot Conferences on Poromechanics*, Paris, France, July 9-13, 2017.

Root, K., Guo, Q., Quiel, S., 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, Accepted January 2018.

Wu T, Mooney M and Nazem A. (2018). Stability of foam conditioned soil in the EPB TBM chamber. *Proc. World Tunnels Congress*, Dubai, Apr 22-26, 2018.

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

The UTC-UTI website 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; 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 have given *presentations in the UTC-UTI sponsored/co-sponsored seminar series*, and the *First UTC-UTI Workshop*.
- Jacobs Engineering North America Building and Infrastructural (Pasadena, CA)
- CDOT (Denver, CO, and Golden, CO)
- The Robbins Company (Solon, OH)
- Mine Site Technologies Global (Golden, CO)
- Kiewit Infrastructure Co. (Omaha, NE)
- Hecla Mining Ltd. (Coeur d'Alene, ID)
- Ohbayashi Corp. (Burlingame, CA)
- Graphic Schedule (Arroyo Grande, CA)
- Michels (Brownsville, MI)
- California High Speed Rail Authority (Sacramento, CA)
- Mott MacDonald (Birmingham, AL)
- Arup (New York, NY)
- Stantec Engineering (San Diego, CA)

b) Representatives from the following organizations are *members of the UTC-UTI Advisory Board*:
- Colorado DOT (Denver, CO)
- Federal Highway Administration (Washington, DC)
- Mott MacDonald (Millburn, NJ)
- Council of University Transportation Centers (Washington, DC)
- Arup (New York, NY)
- Penn DOT (Harrisburg, PA)
- WSP/Parsons Brinckerhof (Chicago, IL and Washington DC)
- Tongji University, China (Shanghai, China)

c) The following organizations have committed to *provide cash or in-kind cost-match to UTC-UTI projects*:
- CDOT (Golden, CO)
- RAMAX LLC (Lakewood, CO)
- IET Waterjet Foundation (Golden, CO)
- MapTek (Golden, CO)
- Tongji University (Shanghai, China)
- Jay Dee Contractors (Seatle, WA and Lakewood, CO)
- Sound Transit (Seattle, WA)
- L-7 Services, Golden, CO
- Traylor Brothers Inc., Los Angeles, CA
- WSP, Los Angeles, CA

d) Representatives from the following organizations *assisted in the organization of the First UTC-UTI Symposium* to be held in September 21-22, 2017:

- Federal Highway Administration (Washington, DC)
- C.W. Felice, LLC (Kirkland, WA)
- Pennsylvania DOT (Harrisburg, PA)

3.2 Have other collaborators or contacts been involved?

a) CSM has been in continuous contact with CDOT, industry and academe on potential collaborations and co-funding of UTC-UTI efforts. Outcomes of discussions include a collaborative proposal with CDOT on the extension of the Eisenhower-Johnson Mountain Tunnel, 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.

b) CSULA has been in discussion with the Los Angeles County Infrastructure Initiatives to establish guest speaker series, site visits, and industry professional development efforts. CSULA has also been in contact with Caltrans (Jim Appleton - Division Chief, Division of Research, Innovation and System Information) for potential collaborations.

c) Lehigh continued their efforts in engaging the industry (e.g., Encon United and for the Seattle State Route 99 Tunnel Project) and PennDOT.

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 23 students and three postdocs were supported by UTC-UTI through 15 research projects. UTC-UTI also continued to hold outreach and recruiting initiatives aimed at encouraging undergraduate students to pursue advanced degrees in Underground Transportation Infrastructure.

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. One activity from this reporting period, which illustrates UTC-UTI's strong commitment to technology transfer was the First Symposium on Underground Transportation Infrastructure with a theme of "*Challenges and Opportunities for Underground Transportation Infrastructure in the US*." The symposium had 47 participants including 27 from the industry and government agencies and highlighted presentations from leading experts in the field, work being carried out by UTC-UTI and research needs in UTIs. The Center also held in *First Workshop* with focus on its current research projects with a view of identifying synergies and potential areas of collaboration between researchers. UTC-UTI PIs have also been very active in pursuing potential collaborative projects that are of value to the industry and DOTs.

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

UTC-UTI is now recovering from the initial delay in starting its research activities due to difficulty in recruiting graduate students and postdocs. The Center is now working with a full complement of personnel. Research work is now in full swing and are starting to produce valuable results.