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

1.2 Progress and Accomplishments

1.2.1 Research Activities

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

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

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

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

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

project team. (Obj. 2) The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is complete and 3D finite element modeling is in progress. (Obj. 3) The analysis of LA metro cavern excavation data coupled with real time computational modeling is ongoing.

MILESTONES ACCOMPLISHMENTS AND DATES: As of March 31, 2019: For objective 1, one conference paper have been written and published, a second conference paper has been written and submitted, and two journal papers are under development. For objective 2, one conference paper has been written and published. For objective 3, PhD student Haotian Zhang was embedded in LA with the construction team July 2018 to March 2019 and successfully forecasted cavern deformation accurately. That phase has been completed. Computational modeling is ongoing.

PLANNED ACTIVITIES: NEBT tunnel analysis will ramp up and LA Metro study will be completed in the next year. We aim to develop a traceable and objective procedure to identify reliable ground properties based on field measurements from cavern sequential construction.

PROJECT PERSONNEL: Dr. Mike Mooney, Dr. Marte Gutierrez, PhD students Tamir Epel and Haotian Zheng.

TITLE OF THE PROJECT: Functional reliability of tunnels and its impact on transportation network resilience

SUMMARY: Tunnels are typically one of the most critical links in a transportation network and they greatly undermine network resilience when they lose functionality (either entirely or partially) due to hazardous loading conditions. Closure or limited access of traffic tunnels (function loss) is very costly and has great negative impacts on the public. Each tunnel owner or manager typically analyzed these events in a case-by-case basis. There is currently a lack of systematic data collected or analysis done to 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 is 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. These intermediate findings have been summarized into papers and presentations and submitted to professional conferences and workshops. The development of a probabilistic simulation framework with several modules for tunnel infrastructure resilience is underway. The student has completed the module for tunnel functionality loss related to fire events and is now working on simulation of tunnel closure for hazardous material truck groups.

MILESTONES ACCOMPLISHMENTS AND DATES: No significant milestone was reached during the reporting period.

PLANNED ACTIVITIES: The research team plan to develop a probabilistic simulation framework that can simulate tunnel closures (partial or complete) over a long period of time for any given tunnel configuration inputs and environmental inputs (such as weather, traffic condition, etc.). The module for this simulation tool related to fire-induced closure has been programmed. Other modules such as closure due to hazardous material truck group, maintenance, crash, structural and mechanical failure will be developed in the following months.

PROJECT PERSONNEL: Marte Gutierrez, Shiling Pei, and Sandeep S Khetwal (Graduate Student).

TITLE OF THE PROJECT: Probabilistic rock mass quality prediction model and its application to tunneling design

SUMMARY: Uncertainties in a rock mass quality measure are due largely to the inherently heterogeneous nature of the rock mass itself. Traditional deterministic methods for the assessment of rock mass quality are not based upon a complete understanding of these inherent uncertainties, which can result in adverse impact on overall design performance. To address this problem, a Monte Carlo simulation (MCS)-based uncertainty analysis framework is proposed to probabilistically quantify the uncertainties in the Q-system of rock mass classification. The proposed framework is then implemented in a highway tunnel case study. The probability distribution of the Q-value is obtained using the MCS technique in which the relative frequency histograms of the input parameters are used to probabilistically assess the rock mass properties and responses with appropriate empirical correlations. The probabilistic estimates of the rock mass properties are also adopted as the input for a finite element model for a probabilistic evaluation of the excavation-induced tunnel displacement. In addition, a probabilistic sensitivity analysis is conducted to rank the relative importance of the input parameters in the Q-system according to the regression coefficients, Spearman's rank-order correlation coefficients, contributions to variance and effects on output mean. The effects of the distribution types of uncertain input parameters in the Q-system are also examined. The proposed framework is shown to be capable of systematically assessing the uncertainty in the rock mass quality measure before construction as well as providing insightful information for the probabilistic evaluation of the ground response and support performance of underground structures.

PROJECT STATUS: This project has started in January 2017 and completed case studies of Hong Kong using Marco-chain method. We propose a probabilistic Q-based prediction model using MCS technique reflects the uncertainty and applied to the Shimizu Tunnel case study.

MILESTONES ACCOMPLISHMENTS AND DATES: This project has started in January 2017. The Marco chain algorithm was developed for analyzing a Hong-Kong project. A probabilistic Q-based prediction model using MCS technique also is developed. Reliability analysis on Shimizu Tunnel case study has been underway since February 2019.

PLANNED ACTIVITIES: We will complete the predicted probabilistic Q using a 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: Physical modeling to study tunnel squeezing under true-triaxial stress state

SUMMARY: Squeezing rock conditions have been causing significant 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 that would promote the squeezing ground behavior. The mechanism of squeezing failure of tunnels is not clearly understood, and the goal of this research project is to understand better the causes leading to squeezing ground phenomena. The objectives are to (a) identify the major causes of squeezing in soft rock; (b) quantify the squeezing rates and amounts: and (c) develop experimentally verified squeezing criterion for broader application to tunnels. To achieve the research objectives, a series of novel true-triaxial compression experiments with simultaneous tunneling in rock are being conducted.

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

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Development of the experimental setup for true-triaxial testing of rock blocks (December, 2017); (2) selection of rock-like materials for batching and mixing to simulate the rock formation (September, 2018); (3) design and fabrication of a tunnel boring machine for tunnel excavation while the rock is subjected to the true-triaxial state of stress (January, 2019); (4) physical modeling to study behavior of lined tunnels in squeezing ground conditions (March, 2019).

PLANNED ACTIVITIES: Research plan for this year onward will be to perform experiments involving physical simulation of tunnel excavation in cubical rock specimens loaded in the true-triaxial cell using a fabricated tunnel boring machine.

PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Reza Hedayat and Ph.D. 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 densely populated urban areas. Tunnels are often constructed close to the surface, increasing the likelihood of excavation induced ground subsidence. It is therefore necessary to quantify tunneling-induced ground surface deformation. 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 processing data to investigate deformation during construction of the Seattle Viaduct replacement tunnel. Significant dewatering was required to construct a rescue pit after the Tunnel Boring Machine named Bertha struck a well casing and needed repairs. Specifically, we are investigating subsidence and subsequent rebound using data from the Sentinel-1 A&B satellites. A maximum total deformation of ~3 cm is measured in the satellite line of sight direction. These results highlight the potential use of InSAR as a monitoring tool for underground excavation in terms of determining the water ingress source extent, and for public safety to quickly identify areas at risk of experiencing rapid subsidence.

PROJECT STATUS: Initial efforts to identify tunnel induced surface subsidence using satellite InSAR began in May 2017. These initial efforts focused on developing methodologies better suited for investigating relatively slow subsidence events, for which a journal paper is currently under review. Currently we are attempting to apply this technique to transportation tunnels within the United States.

MILESTONES ACCOMPLISHMENTS AND DATES: We have identified one of the largest and most complete surface deformation signals induced by tunneling to date, developed a new InSAR processing technique designed to remove noise from smaller deformation signals, and are currently applying it to the Seattle Viaduct replacement tunnel in the United States.

PLANNED ACTIVITIES: We plan to continue processing freely available data for studying subsidence in Seattle. Depending on results, it may be necessary to write a proposal to the European Space Agency to acquire higher resolution data from the Cosmo-SkyMed satellite constellation.

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 interpretations of some sparse initial investigations. As a predictive model of the true subsurface geology, a 3D geologic model has potential to aid in improving geologic understanding and to provide a baseline for subsequent design and analysis. The initial geologic model inherits uncertainty from input data and interpretations. As tunneling progresses in a hard rock setting, information on the encountered geologic conditions can be collected prior to installation of the final tunnel support. These new observations can be used to both validate existing geologic models and update model uncertainty to account for previously unseen structures. During excavation, this information can

be used to adapt the geologic model to unfolding ground conditions and following excavation the calibrated geologic model can be used to inform potential expansions near the existing tunnel alignment. Model discrepancy is used to formulate and assess predictions of subsurface geology in the context of a 3D geologic model. Bayesian statistics provides a convenient framework for validating and updating predictions of subsurface geology considering new observations and information. The objectives of this project are: 1) To implement a data-driven 3D geologic modeling workflow that predicts geologic structures along a tunnel alignment with quantified uncertainty and 2) To utilize additional information gathered during excavation to adapt the geologic model to encountered geology in a Bayesian framework.

PROJECT STATUS: This project started in May 2017; literature review and initial modeling of datasets from two tunneling projects has been completed as of Fall 2018. Formulation and implementation of geologic model uncertainty assessment using an input-based, model discrepancy approach is underway as of Spring 2019.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) A workflow for assessing structural uncertainty of a 3D geologic model has been developed and implemented for two tunneling datasets. (2) A formal proposal of the research has been prepared for defense to a PhD thesis committee.

PLANNED ACTIVITIES: (1) Quantification of geologic model uncertainty and analysis of model sensitivity to various input data and interpretations. (2) Formulation of geologic model validation and updating using Bayesian inference. (3) Combined modeling of geologic properties within a structural 3D geologic modelPROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez and PhD student Ashton Krajnovich.

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

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

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

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

PLANNED ACTIVITIES: The MS project will be complete as of May 2019, by which time Max Mifkovic will have defended and submitted his thesis. A journal publication based on this thesis work will also be submitted in the next six months.

PROJECT PERSONNEL: Dr. Andrei Swidinsky, Dr. Michael Mooney and graduate student Max Mifkovic (MS program started September 2017).

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

SUMMARY: To circumvent the technical and operating challenges associated with the conventional removal and repair of shotcrete and concrete liners from underground workings, this research seeks to develop an innovative system that utilizes high pressure waterjet technology as the primary excavation tool. The 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 using strategically positioned accelerometers mounted to the imbedded rebar. An analysis of the vibration data showed approximately an order of magnitude reduction in acceleration during cutting for the waterjet system, as compared to mechanical excavation. GPR data collection was complete and has undergone several iterations of analysis. While the GPR scans proved helpful in visualizing rebar location within each panel, the interpretation of the data to delineate differences between the excavation methods and the unintended damage to the test blocks has been inconclusive to date. Efforts to further analyze this data will be an important objective of an Ph.D. dissertation associated with this research. Physical inspection of the test panels for peripheral damage to the substrate and adjacent shotcrete around each excavation was performed to identify cracks, delamination, and damage to the wire/rebar. The mechanically excavated panels suffered significant collateral damage, where in contrast, the waterjet kerfs exhibited no detectable damage. The empirical results from laboratory testing strongly indicate that waterjet removal causes significantly less collateral damage to adjacent material and the delamination between the shotcrete and the substrate.

PROJECT STATUS: The research project started in May 2017. The project received a no cost extension, where the final report is currently nearing completion (May 2019). A Ph.D. dissertation is being prepared in parallel with this research which facilitated additional laboratory testing in January and February 2019 to provide supplemental data. All mechanical and waterjet shotcrete cutting tests associated with the project have been completed. Vibration data collected during the cutting tests for both mechanical and waterjet excavation have been analyzed, where the results have been included into the draft final report. Test panels were scanned with ground penetrating radar (GPR) before and after excavation. The GPR data analysis and related physical inspection of the test panels have been completed, where analysis of the GPR data will continue as part of a Ph.D. research project. The final report is currently nearing completion and will be submitted in May 2019.

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 was complete in October 2018. (7) Visual inspection for the kerfs generated by each excavation methods for each test sample blocks were completed in November 2018. (8) GPR scans of the test panels were finished in

October 2018 and data analysis continued into March 2019. (9) The writing of the final project report is scheduled for completion by May 2019. (10) Building on this research, a Ph.D. Thesis dissertation is scheduled for completion in March 2020.

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

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

Research at California State University Los Angeles

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

SUMMARY: This 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: Phase I and Phase II of the first objective are complete. In Phase III, we visualized the results. We are working on refining the predictive model to achieve even more accurate results. We used a big dataset from a 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. The latest results were presented in the UTC-UTI workshop in Oct. 2018. For the second objective, we have recently developed our first model for adverse event prediction and anomaly detection based on deep neural networks. The model is now under training to achieve more accurate results and predict wider range of adverse events.

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. Phase III has started in Fall 2018 and is still in progress. The preliminary results have been presented in UTC-UTI workshop (Feb. and Oct. 2018). Objective II, Phase I has started in Fall 2018, and the very first predictive model has been recently developed.

PLANNED ACTIVITIES: (1) Defining and including a wide range of anomaly and adverse events for our predictive model; (2) Developing new methods based on more complex deep learning models that can take into account more data elements to achieve higher accuracy levels; (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; (4) Developing, training, and applying the proposed method on other datasets; (6) Publishing and presenting the results in the form of conference and journal papers. As for journal

publications, we are under waiting period to get approval from the tunneling project contractor for publishing the results.

PROJECT PERSONNEL: Mohammad Pourhomayoun (PI), Mehran Mazari (Co-PI), Luis Fisher (MS CS Student), Kabir Nagrecha (BS CS Student).

TITLE OF THE PROJECT: Resilience and sustainability of underground transportation infrastructure

SUMMARY: The goal of this study is to assess to what extent existing guidance for sustainable and resilient infrastructure design is appropriate for use with 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: The following tasks have been completed: (a) a literature review in the areas of (i) guidance for transportation infrastructure, (ii) guidance for climate vulnerability assessments, (iii) rating systems, and (iv) underground-specific guidance; (b) an assessment of the Climate Change & Extreme Weather Vulnerability Assessment and Scoring Tool (VAST) proposed by the Federal Highway Administration (subjecting representative UTI assets to storm surge and sea level rise); and (c) an assessment of the ISI Envision Rating System for a representative UTI project.

MILESTONES ACCOMPLISHMENTS AND DATES: The vulnerability assessment of underground assets using the VAST tool has been published and presented at the 2018 International Conference on Transportation and Development (July 2018). The literature review and the assessment of Envision have been completed and accepted for presentation and publication at the 2019 International Conference for Sustainable Infrastructure. The final paper has been finished, submitted, and accepted (April 2019).

PLANNED ACTIVITIES: The current ongoing activity is assessing the applicability of the LA Metro Resiliency Indicator Framework for UTI. 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: Tonatiuh Rodriguez-Nikl (PI), Mehran Mazari (co-PI)

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 use, is important for safety, performance, liability, and cost. The goal of this project is to develop a fully automated system to perform continuous monitoring of tunnels during and after construction. The following 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 in 2017. Based on its performance a second prototype was developed using commercial, off the shelf equipment, including

a DLSR camera with high intensity LED arrays and synchronized flash lights in 2018. The convolutional neural network (CNN) was trained based on the acquired image database achieving a 97.8% accuracy in automated detection of cracks and other blemishes. Acquired images need to be tagged with location information within the tunnel. Multiple approaches are currently under study for localization within tunnels and other underground infrastructure in the absence of any GPS, WiFi or any other beacon signal which may be used to define reference locations. A promising approach currently being explored is Simultaneous Localization and Mapping (SLAM) which is under extensive study for Autonomous Vehicle operation, but clearly applies to the application at hand.

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 completed in summer 2018. Training of the deep CNN based on Google's inception V4 was completed by the end of Fall 2018 leading to the 97.8% detection result reported.

PLANNED ACTIVITIES: (1) design and development of an inertial navigation system based on SLAM for inside tunnels and synchronous tagging of the images with geo-location information; (2) optimization and integration of several complex algorithms for implementation of SLAM (Kalman and Particle filtering, interval constraint propagation, MAP, etc.); (3) exploration of stereo-image based techniques for implementation of SLAM.

PROJECT PERSONNEL: Fred Daneshgaran (PI), Marina Mondin (co-PI), Antonio Marangi, Nicola Bruno, and Fausto Lizzio, all students are from Politecnico Di Tornio, Turin, Italy (Visiting scholars at CSULA, all pursuing MS in Mechatronics), Brian Martinez, CSULA student pursuing MSEE degree.

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

SUMMARY: Self-Consolidating Concrete (SCC), also known as self-compacting concrete, is a type of hydraulic cement concrete that easily forms around the reinforcement without segregation. Design of an SCC mix is chosen based on either powder-type, viscosity modifying admixture-type, or a mixture of the two types depending on structural and constructional conditions, and material available. Due to the improved fresh properties of SCC, this concrete type is more favorable for precast sections that could be used in transportation infrastructure applications. The main objective of this study is to investigate the effect of fiber-reinforcement on fresh and hardened properties of the SCC. The fiber type and content in the SCC mix, affect the compressive strength, tensile strength and crack initiation and propagation. The improved mechanical properties of the fiber-reinforced SCC make it an alternative solution for pre-cast sections for transportation infrastructure applications compared to the conventional concrete. The other objectives of the research are: (a) review of literature to study the application of self-consolidating concrete for underground infrastructures, (b) evaluating fresh and hardened properties of self-consolidating concrete, (c) evaluating the use of recycled fibers to improve the properties of self-consolidating concrete, (d) investigating the use of sustainable materials (i.e. fly ash and slag) to reduce the amount of cementitious materials in self-consolidating concrete, and (e) evaluating the crack initiation and propagation related to properties of the self-consolidating concrete.

PROJECT STATUS: The project is in Phase II. Fiber-reinforced SCC specimens are prepared in the laboratory conditions using different types of manufactured and recycled fibers. The effect of non-cementitious material replacement on fresh and hardened properties of SCC mixes are being evaluated. The analytical models are calibrated and being improved to increase the accuracy. Preparation for casting the fiber-reinforced beam specimens are undergoing.

MILESTONES ACCOMPLISHMENTS AND DATES: Two papers from this project were presented in the Transportation Research Board annual meeting and the ASCE International Conference on Transportation and Development.

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 published in the Transportation Research Record in September of 2018. In a similar manner, Rhinoceros and Grasshopper have been utilized further to create a visual tool for calculating thermal demands on a tunnel liner for given fire sizes. Accepted structural fire design criteria are leveraged in the intermediate modelling process. Again, computationally intensive modelling with the Fire Dynamics Simulator (FDS) software package is utilized for validation of the intermediate approach. FDS models are compared against existing experimental work by others for validation of applicable fire hazard effects in the tunnel environment. This work was presented at the 10th International Conference for Structures in Fire (Sif18) in Belfast, Northern Ireland in June 2018 as well as the TRB Annual Meeting in Washington, DC in January 2019. A manuscript was submitted to Fire Safety Journal in February 2019. Ongoing efforts are being focused on analysis of representative tunnels subject to blast loads using numerical models to examine the resilience of ancillary structural components of the tunnel. A comprehensive probability-based framework is being used to examine the cost/benefit performance of various size vehicle threats.

MILESTONE ACCOMPLISHMENTS AND DATES: (1) Literature review and database – May 2017. (2) Establishment of tunnel prototypes – June 2017, (3) Evaluation of prototypes to near field blast effects and conference summary paper – August 2017, (4) Presented rapid blast damage prediction tool at TRB Annual Meeting – January 2018, (5) Acceptance of blast paper to Journal of the TRB – March 2018, (6) Evaluation of prototypes to radiation and convection from severe fire and summary conference paper – March 2018, (7) Presentation at SiF18 June 2018, (8) Refinement of fire models to account for variation in tunnel geometry (rectangular, horseshoe, round), mesh sensitivity, and fire size – June to August 2018, (9) Submitted TRB paper on predictions for fire induced spall - August 2018, (10) Developed estimates of gas pressure overload generated from accidental explosions in tunnels - September 2018 through March

2019, (11) Presented rapid fire damage assessment tool at TRB Annual Meeting - January 2019, (12) Awarded $30,000 from the Pennsylvania Infrastructure Technology Alliance (PITA.org) to leverage UTC-UTI funds toward the investigation of blast effects on false ceilings in tunnels – January 2019. (13) Submitted journal manuscript to Fire Safety Journal regarding the rapid-fire damage assessment tool – February 2019. (14) Acquired sample tunnel structural drawings from DOT collaborators from Oregon and Pennsylvania January 2019.

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

PROJECT PERSONNEL: Ph.D. student Qi Guo, Ph.D. student Aerik Carlton, M.Sc. student Ziyan Ouyang, Faculty Dr. Spencer Quiel and Dr. Clay Naito.

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

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

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

The behavior of concrete lining under fire conditions is being investigated both numerically and experimentally. An experimental program was initiated to investigate the effect of pertinent parameters on the propensity of thermal spalling, including rebar density, applied axial stress, and magnitude of thermal exposure. Fabrication of the experimental test set up has been completed. The test setup has been calibrated, and preliminary tests have been performed. Test data will be coupled with the computational models to examine the growth of pore pressure as well as mechanical stresses through the thickness of the panel in relation to the fire severity. Preliminary spalling evaluations have been integrated with the total damage mapping tool developed from the Lehigh team's other UTC-UTI project, which will be capable of conservatively predicting tunnel liner damage for a given fire event.

A conference call was held on August/21/2018 with seven state DOT representatives from the AASHTO T20 committee to discuss the current progress of this project and identify related topics of interest. The

committee members highlighted several areas of research interest, including the blast and fire resistance of false ceiling and ventilation structures as well as tiles and other coatings applied to the tunnel liner. The Lehigh team is actively incorporating the T20 guidance into their planned research and has been receiving information and feedback from several members of this group.

MILESTONES ACCOMPLISHMENTS AND DATES: The major remaining task is the enhancements made to fire-induced spalling test setup to increase the range of fire exposure for larger events to be completed in March 2019.

PLANNED ACTIVITIES: (1) Investigate spall damage mechanism due to fire hazard by performing concrete spall tests and multi-physics numerical simulation. (2) Conduct parametric numerical analysis of panels to assess fire induced spall performance of liner segments. (3) Complete blast sensitivity study to illustrate the influence of substrate on blast damage of liners. (4) Design prototype liner system that benefits from substrate blast pressure dampening and spall resilience. (4) Develop a blast and fire test validation program to verify performance of design.

PROJECT PERSONNEL: Ph.D. student Qi Guo, Ph.D. student Aerik Carlton, M.Sc. student Ziyan Ouyang (started September 2018), Faculty Dr. Clay Naito and Dr. Spencer Quiel, an offer was made to bring on a new Ph.D. student starting in July 2019, the student will make a decision of whether to accept by the end of April 2019.

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 31 students (13 PhD, 7 MS and 11 BS) are funded by UTC-UTI. Of which 20 (11 PhD and 9 BS) are working at CSM, 8 (6 MS and 2 BS) at CSULA, and 5 (2 PhD, 1 MS and 2 BS) at Lehigh. All graduate students actively worked on their thesis and dissertations and are progressing towards the completion of their degrees. 11 REU (Research Experiences for Undergraduate) students assisted the graduate students in their research. Students participated in all aspects research and outreach of the including design of experiments, computational modeling, data analysis, field surveys, project presentations and report writing. One M.Sc. at Lehigh University graduated in Fall 2018, and another MS student at CSM will graduate in Spring 2019.
b) UTC-UTI students co-authored papers and participated and made presentations in several conferences including the *2019 Society of Mining, Metallurgy, and Exploration* (SME) in Denver, CO, February 26, 2019; *TRB Annual Meeting* in Washington DC, January 10, 2018 including *TRB Committee Meetings*; *Cal State LA Research Symposium* in February 22, 2019; and *University of Southern California Research Seminar;* and *Hispanic Engineer National Achievement Awards Corporation (HENAAC) Conference* in Pasadena, CA, October 17, 2018.
c) 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
d) One graduate student participated in project meetings and site visits with CDOT to collect tunnel operational data at the Eisenhower-Johnson Memorial Tunnel (EJMT).
e) A CSM PhD student carried out a research internship on the LA Regional Connector Project from July 2018 to March 2019. The student is embedded with the cavern excavation team on the project, enabling him to best carry out his PhD research.
f) Three graduate students and two undergraduate students were involved in data gathering in connection with the engineering feasibility study of the future extension of the EJMT.

g) One CSM Ph.D. student collaborated with Seequent, developers of the Leapfrog implicit geologic modeling software for automated assessment of geologic model uncertainty
h) A PhD student participated in activities associated with the use of the RAMAX Laboratory in California and assisted with the waterjet cutting tests.
i) 13 CSULA students received the Eisenhower Transportation Fellowship and attended Transportation Research Board Annual Meeting in Washington DC in January 2019.
j) Two CSULA students received the TRB Minority Fellowship award, presented their papers at the TRB Annual Meeting and attended the Chairman Luncheon.
k) CSM PhD student Ashton Krajnovic awarded a $500 prize for best PhD Student presentation during the CSM Geology and Geological Engineering 2019 Research Fair in February 2019.

1.2.3 Outreach Activities

a) UTC-UTI organized and held the *Workshop on Performance of Underground Transportation Infrastructure: Opportunities and Challenges* during the TRB Annual Meeting in Washington, DC, on January 13, 2019. This workshop was co-sponsored by the Committee AFF60 Tunnels and Underground Structures Committee and University Transportation Center on Underground Transportation Infrastructure. There were nine presentations and about 30 participants from the academe and industry.
b) 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).
c) UTC-UTI researchers continued to actively participate in several Technical Committees in AASHTO, TRB, ASCE, ARMA and other professional organizations.
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. Mike Mooney UTC-UTI Associate Director launched a *Teach the Professors program for Civil Underground*. 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.
f) Dr. Reza Hedayat has been selected by the *American Rock Mechanics Associations (ARMA) Board of Directors* to establish an ARMA technical committee on Tunneling. During this period, Dr. Hedayat has initiated the discussions with other existing technical committees in ARMA and will be soliciting interest from ARMA members to join the committee.
g) The Lehigh team organized a conference call on August 21, 2018 with the *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.
h) CSULA researchers organized presentation from Industry partner (Kiewit) on Transportation Infrastructure Construction on Cal State LA's campus.
i) CSULA continued to reach out to LA Metro Rail to collect new big datasets for training, modeling and validating the developed algorithms.
j) Dr. Andrei Swidinsky organized a *Session on Geophysics for Underground Tunneling at The Society of Exploration Geophysics Annual Meeting in Anaheim*, CA, October 14-19, 2018.
k) In February 2018, Dr. Hugh Miller began a 3-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*. Miller also became the 2019 SME President beginning in February

2019. During this reporting period, Hugh Miller and the project team have participated in several industry short-courses, invited talks, and conference events.

1.2.4 Leveraging UTC-UTI Funds [i]

Extensive efforts have been made by UTC-UTI PIs to engage the industry, State DOTs and other partners in leveraging UTC-UTI funds to generate additional funding 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. The project team obtained historical data (paper logs) from EJMT from CDOT and converted close to one year of such data into an electronic data set to be used for simulation model validation. The project team also met and discussed with CDOT tunnel office on the potential to further mine the CTMS database, which is a dedicated transportation accident/event management system used by CDOT. Basic information about the system was obtained and the team plan to further inquire the access to this database once the simulation model is established.
b) CDOT has provided $100,000, 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) Tongji University in China provided valuable data on the construction of MuZhai Ling Tunnel in China, and extensive data on the operation and maintenance of subway tunnels in Shanghai, China.
d) Data sets and project personnel from two tunneling projects, LA Metro Regional Connector and Seattle Sound Transit, contributed extensively to this project during this period.
e) Skanska Construction Company provided $13,500 to support PhD student Haotian Zhang's living expenses in carrying out his field research on the LA project site.
f) Jay Dee Contractors provided in-kind support valued at $87,500 for the Seattle Northlink project analysis.
g) Lane Construction company is providing access to extraordinary instrumented segmental lining load processes and data.
h) An REU (Research Experiences for Undergraduates) site proposal, based on the research being carried out by UTC-UTI, is currently under evaluation for consideration for funding at the National Science Foundation (NSF). The proposal has finished the review process and according to the NSF Program Director, the proposal was placed in the "Fund if Possible" category. UTC-UTI will plan for resubmission of the proposal addressing the comments in Summer 2019 if the proposal is not funded by NSF.
i) A portion of academic year salary cost share for Lehigh faculty members Dr. Spencer Quiel and Dr. Clay Naito for their time devoted to the research efforts is provided. A 50% tuition discount was provided for the support of both PhD students. A University tuition scholarship was provided for the MS student who graduated in September 2018.
j) Lehigh University was awarded $30,000 from the Pennsylvania Infrastructure Technology Alliance (PITAPA.org) to leverage UTC-UTI funds in collaboration with Pennsylvania Department of Transportation toward the investigation of blast effects on false ceilings in tunnels – January 2019.
k) Cal State LA was recently selected to receive two awards ($150k total) from California State University Transportation Consortium with support from Caltrans and California Transportation Foundation. Dr. Mehran Mazari is the PI and Co-PI on these two awards.

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) In December 2018, Dr. Hugh Miller received the prestigious *Medal of Merit Award by the American Mining Hall of Fame f*or his contributions to Mining Education. He also gave an invited presentation to the Society of Economic Geologists, CSM, November 8, 2018.
b) Cal State LA was recently awarded the *2019 National Summer Transportation Institute.*
c) Professor Clay Naito was invited to the National Research Council of Canada (NRC) *International Workshop on Protection of Critical Infrastructure Against Close-By and Attached Explosives* on March 28-29, 2019 in Ottawa Canada. He presented an overview of the UTC-UTI effort underway and shared preliminary results on LU research projects funded by UTC-UTI. All costs of the effort were covered fully by the NRC (no costs were incurred to the UTC-UTI).
d) Dr. Marte Gutierrez was Keynote Lecturer in *2019 Conference on Plasticity, Damage and Fracture*, Panama City, Panama, January 3-9, 2019. He was Member of the Scientific Committee of *Computational and Geoenvironmental Geomechanics for Underground and Subsurface Structures (COGGUS)*, Nancy, France, February 12-14, 2019; and of the Organizing Committee of *IS-Atlanta-Geomechanics from Micro to Macro*, Atlanta, GA, September 10-13, 2018. He also gave invited presentations at six different universities.
e) Dr. Mike Mooney delivered an Invited Lecture on Artificial Intelligence and Physical Model Based Performance Prediction of EPB TBM Tunneling at the *Tunneling & Underground Construction Society*, Singapore, November 15, 2018.
f) Dr. Mehran Mazari of Cal State LA was appointed as the Co-Chair of *Long-Term Pavement Performance (LTPP) Data Analysis Contest* subcommittee of *Highway Pavement Committee – ASCE Transportation and Development Institute*.
g) Dr. Clay Naito at Lehigh University accepted or published 11 journal papers, 2 conference papers, and gave 7 presentations between May 2018 and April 2019.
h) Dr. Spencer Quiel at Lehigh University accepted or published 11 journal papers, 3 conference papers, 1 magazine article, and gave 4 presentations between May 2018 and April 2019.

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/.

Final Research Report:
UTC-UTI has completed its first Final Research Report which has been posted in Zenodo as: https://zenodo.org/record/2641069#.XL3tRuhKiUk, and submitted to various Federal reporting sites.

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:

Hou, Z. Gutierrez, M., Wang, A., Almrabat, A. and Yang, C. (2018). Mechanical Properties and Brittleness of Shale with Different Degrees of Fracturing-Fluid Saturation. *Current Science*, 115(6), 1163-1173.

Kamali-Asl, A., Ghazanfari, E., Hedayat, A., and Deering, L. (2018). Investigation of Static/Dynamic Moduli and Plastic Response of Shale Specimens. *International Journal of Rock Mechanics and Mining Sciences*, 110, 231-245

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

Kravitz, B., Mooney, M., Karlovsek, J., Danielson, I., and Hedayat, A. (2019). Void Detection in Two-Component Annulus Grout Behind a Pre-Cast Segmental Tunnel Liner Using Ground Penetrating Radar. *Tunnelling and Underground Space Technology*, 83, 381-392.

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*, 5(2), 1-9.

Maruvanchery, V. and E. Kim (2019) Effects of Water on Rock Fracture Properties: Studies of Mode I Fracture Toughness, Crack Propagation Velocity and Consumed Energy in Calcite-Cemented Sandstone. *Geomechanics and Engineering*, 17(1) 57-67.

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.

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

Yu, Y., Workman, A., Hering, A.S., Mooney, M.A. and Grasmick, J. (2018). Space-Time Outlier Identification in a Large Ground Deformation Dataset. *Journal of Quality Technology*, 50(4), 431-445.

Selected Conference Papers and Presentations:

Prassetyo, S.H. and Gutierrez, M. (2018), Integration of Analytical, Empirical, and Numerical Methods in Analyzing Support Requirements for Tunneling in Weak Rock. *Geomechanics and Geodynamics of Rock Masses*, Livitnenko, V. (ed.), *Proc. European Rock Mechanics Symposium (EUROCK 2018)*, May 21-27, 2018, Saint-Petersburg, Russia, pp. 1191-1197.

Wnuk, K., Zhou, W. and Gutierrez, M. (2017). Using InSAR Time Series Analysis to Characterize Tunnel Induced Surface Deformation. *Association of Environmental and Engineering Geologists Annual Meeting*. Colorado Springs, CO. September 15th, 2017.

Bourgeois, J., Miller, H., Steele, J., B., Charrier, E., and Asbury, B. (2019). The Characterization of Delamination Processes with Respect to Waterjet Shotcrete Removal during Tunnel Liner Repair and Maintenance", *2019 TRB Annual Meeting*, Washington DC, January 2019.

Mifkovic, M., Swidinsky, A., & Mooney, M. (2018). Imaging ahead of tunnel boring machines with DC resistivity: A laboratory study. *SEG Conference*, Anaheim, CA, October 14-19.

Daneshgaran, F., Zacheo, L., Di-Stasio, F., and Mondin, M. (2019). Use of deep learning for automatic detection of cracks in tunnels – Prototype-2 developed in the 2017-2018 time period. *2019 TRB Annual Meeting*, Washington, D.C.

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

Marquez, D., Ojeda, F., Cruz, H., NG, J., Mazari, M. (2019). Evaluating Fresh and Hardened Properties of Fiber Reinforced Self-Consolidating Concrete for Transportation Infrastructure Applications. *2019 TRB Annual Meeting*, Washington, D.C.

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

Guo, Q., Root, K., Quiel, S.E., Naito, C.J. (2019). Streamlined Calculation of Fire-Induced Heat flux and Resulting Spalling Damage for Concrete Tunnel Liners. *2019 TRB Annual Meeting*, Washington, DC.

Naito, C. (2019). Performance of Transportation Tunnels Subject to Close-In Detonations. Presentation, NRC-CNRC International Workshop on Protection of Critical Infrastructure Against Close-By and Attached Explosives, March 2019, Ottawa, Canada.

Lu, H., E. Kim, and M. Gutierrez (2019). Probability-Based Uncertainty Analysis of Rock Mass Quality in Underground Excavations. *SME 2019 Annual Meeting*, Denver, Colorado, Feb. 26, 2019

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

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

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 (Shanghai, China).

b) The following organizations *have provided cash or in-kind cost-match to UTC-UTI projects*: 1) CDOT (Golden, CO); 2) RAMAX LLC (Lakewood, CO); 3) IET Waterjet Foundation (Golden, CO); 4) MapTek

(Golden, CO); 5) Tongji University (Shanghai, China); 6) JayDee Contractors (Lakewood, CO); 7) LA Metro (Los Angeles, CA); 8) Skanska Construction Co. (Los Angeles, CA); 9) Seattle Sound Transit (Seattle, WA); 10) University of British Columbia (Vancouver, Canada); 11) Lane Corporation (Washington, DC); 12) Pennsylvania Infrastructure Technology Alliance (Pittsburgh, PA); 13) California State University Transportation Consortium (San Jose, CA); 14) Seequent (Broomfield, CO).

c) Representatives from the following organizations have *given presentations in the UTC-UTI co-sponsored seminar series*: 1) Norwegian University of Science and Technology (Trondheim, Norway); 2) CDOT Central 70 Project (Denver, CO); 3) Herrenknecht (Singapore); 4) CDOT (Golden, CO); 5) Arup (New York City; NY); 5) Hatch (Toronto, Canada); and 6) Brierley Associates (Denver, CO).

3.2 Have other collaborators or contacts been involved?

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

4. IMPACT

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

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

4.2 What is the impact on other disciplines?

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

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

A total of 31 students and three postdocs were supported by UTC-UTI through 164research 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 included: 1) *Session on Underground Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course*, 2) *Teach the Professors program for Civil Underground* in June 2018, and 3) *Workshop on Performance of Underground Transportation Infrastructure: Opportunities and Challenges* during the TRB Annual Meeting in Washington, DC, on January 13, 2019.

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.