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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 13 research projects (7 at CSM, 4 at CSULA and 2 at Lehigh). Highlights of these projects are given below.

Research at Colorado School of Mines

**TITLE OF THE PROJECT:** Data-Driven Risk Mitigation of Cross Passage and Cavern Deformation

**SUMMARY:** 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.

**PROJECT STATUS:** (Obj. 1) Seattle Northlink completed (see prior report). Our participation in the NEBT project liner load instrumentation has begun successfully. We will continue this work with the NEBT
The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is complete and 3D finite element modeling is complete. (Obj. 3) The sensitivity analysis and preliminary back analysis procedure for computational modeling inputs are complete, and further reliability analysis for tunneling performance is ongoing.

**MILESTONES ACCOMPLISHMENTS AND DATES:** PhD student Tamir Epel completed the liner loading and cross passage study and final project report and successfully defended his PhD dissertation in March 2020.

**PLANNED ACTIVITIES:** The LA Metro study will be completed in the next reporting period. We aim to develop a traceable and objective procedure to identify sensitive ground properties based on field measurements from cavern sequential construction and provide a reliability-based approach to minimize mutual risk during both tunnel design and construction stages.

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

**TITLE OF THE PROJECT:** Incorporating Spatial Uncertainty to Advance the Practice of Site-Investigations, Geological-Geotechnical Characterization and TBM Performance Prediction

**SUMMARY:** In underground transportation infrastructure (UTI), spatial variability and uncertainty of geological and geotechnical parameters triggers multiple risks. The uncertainty in the geological-geotechnical conditions is largely due to the stratigraphic heterogeneity and inherent soil/rock variability that cannot be fully captured using limited site-investigation data. These unforeseen adverse geological-geotechnical conditions may lead to significant tunneling risks causing reduced tunnel advance rates, schedule delays, cost overruns, and damage to infrastructure and construction equipment. To address this problem, geostatistics-based probabilistic frameworks are proposed to integrate the knowledge of spatial variability and uncertainty into the planning, design and construction activities in soft ground tunneling projects. The objectives of this research are: 1) assess the accuracy of geostatistical models specifically for UTI projects, 2) develop site-investigation framework based on prioritization of UTI project risks, 3) develop a probabilistic framework to characterize the transitional boundary to better characterize tunneling risks, and 4) incorporate geotechnical spatial uncertainty into data drive TBM performance prediction. This research uses geotechnical and TBM data from Anacostia River Tunnel project in Washington DC, North-East Boundary Tunnel project in Washington DC and Northgate Link Tunnel project in Seattle, Washington.

**PROJECT STATUS:** Obj. 1 is about 80% complete. A framework to assess the accuracy of categorical geostatistical models is developed. Evaluation of framework on different geological environments is ongoing. (Obj. 2 is 60% complete. A procedure to identify the priority locations of site-investigation by integrating spatial uncertainty, tunneling risks and project constraints (time and budget) is complete. Identifying an optimal configuration of boreholes to minimize spatial uncertainty is ongoing. (Obj. 3 is 90% complete. A probabilistic framework has been developed to characterize the uncertainty in transitional boundaries within tunneling envelope. Application to better tunneling risk is ongoing. (Obj. 4 is 20% complete. A literature review is complete and setup of the skeletal framework for the problem is ongoing.

**MILESTONES ACCOMPLISHMENTS AND DATES:** PhD student Rajat Gangrade presented a technical paper titled ‘Incorporating Spatial Uncertainty into Site Investigations for Tunneling Applications’ at ASCE Geo-Congress in February 2020.

**PLANNED ACTIVITIES:** Research plan for this year involves working on obj. 4, submitting conference papers and journal articles for obj 1, 2 and 3, and presenting a conference paper at a conference.

**PROJECT PERSONNEL:** Dr. Mike Mooney, Dr. Whitney Trainor-Guitton, PhD student Rajat Gangrade.

**TITLE OF THE PROJECT:** Using InSAR Time-Series Analysis to Characterize Tunnel-Induced Ground Surface Deformation

**SUMMARY:** In December of 2013, Big Bertha broke down approximately 300 m from where it started, requiring major repairs for which a 37m deep shaft was constructed in the fall of 2014. Gaining access to the TBM required significant dewatering at multiple depths ranging from near surface to greater than
Dewatering continued through February 2015, resulting in a 750m by 500m elliptical patch of subsidence with a maximum value of 3.5 cm measured near its center. We are using three separate Sentinel-1 InSAR datasets to verify the location of previously reported subsidence, as well as measure the quantity and spatial extent of post-subsidence rebound.

**PROJECT STATUS**: The current project started in January 2019. All three datasets have been downloaded and undergone automated processing of the InSAR Persistent Scatterers (PS). PS points from ascending and descending datasets were then combined using a newly written script replicating the Minimum Acceleration algorithm used to extract 3D deformation vectors from multiple line of sight InSAR measurements. Final figures are being made and a manuscript is in progress for submission this spring.

**MILESTONES ACCOMPLISHMENTS AND DATES**: 1) Completed Minimum Acceleration algorithm script for extracting 3D displacement vectors (March 2020), 2) Processed Sentinel-1 data covering downtown Los Angeles for project #3 (January 2019), 3) Acquired UAVSAR data covering downtown Los Angeles for project #3 (February 2019); and 4) Proposal for COSMO-SkyMed data covering downtown Los Angeles for project #3 submitted and accepted (March 2020)

**PLANNED ACTIVITIES**: 1) Finish figures and writing a manuscript downtown for project #2 and submit to Nature or Journal of Remote Sensing; 2) Use developed PS scripts to analyze Los Angeles UAVSAR and COSMO-SkyMed data (project #3); and 3) Acquire final UAVSAR dataset and combine with Sentinel 1 and COSMO SkyMed data (project #3).

**PROJECT PERSONNEL**: Dr. Wendy Zhou, Dr. Marte Gutierrez, PhD Student Kendall Wnuk

**TITLE OF THE PROJECT**: Analysis of Ground Deformation Induced by Underground Excavation Using Machine Learning Methods

**SUMMARY**: During the excavation and support of tunnels, changes of stress state in ground mass around the excavation and loss of ground support occur. These changes are typically expressed in the form of ground deformation. For urban tunnel constructions, the ground settlement should be limited within a tolerable threshold to prevent damages to nearby structures. Therefore, analyses and predictions of the ground movement are of great importance both in the design and construction planning periods. The objectives of this project are to: 1) predict ground deformation using machine learning methods. From the monitoring, forward prediction of a ground response can be developed and later be used to provide warnings if the response exceeds system limit. In practice, tunneling-induced ground deformation is mostly estimated via empirical formulations, which does not thoroughly consider influencing factors. Therefore, a reasonable prediction using machine learning methods are of importance. 2) To propose an integrated remote sensing approach combining super-high resolution DigitalGlobe imagery, Interferometric Synthetic Aperture Radar (InSAR) and machine learning methods to monitor deformation caused by underground excavations.

**PROJECT STATUS**: This project has started in September 2019 and has partially completed the two objectives. An improved Back-Propagation Neural Network (BPNN) model has been developed and applied to predict the settlement induced by tunnel excavation.

**MILESTONES ACCOMPLISHMENTS AND DATES**: The optimum network parameters BPNN model has been designed and improved including number of hidden neurons and weight values to achieve the appropriate network intended for modeling the target function. Errors are calculated to evaluate the performance of the improved BPNN model. Errors convergent gradually on the condition with optimum hidden neurons and activation functions. The validated performance show that the predicted settlements from the improved model have good agreements with measurements from in-situ monitoring.

**PLANNED ACTIVITIES**: Further improve neural network model coupling k-fold cross validation method. In addition, a paper associated with this approach will be finished.

**PROJECT PERSONNEL**: Dr. Wendy Zhou, Dr. Marte Gutierrez, PhD Student Linan Liu.
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 has developed a framework for data collection for critical roadway tunnels. The researchers have also visited two major tunnel facilities in CO and interviewed the staff from CDOT. It was discovered that there are no uniform or systematic procedures in existence currently to collect the needed functionality loss data. The project team has processed some historical operation record data from the CDOT tunnels to identify the gap between existing data status to the ideal data structure based on the developed framework. These intermediate findings have been summarized into papers and presentations and submitted to professional conferences and workshops (see below). The development of a probabilistic simulation framework for tunnel infrastructure resilience has just started. Access to CDOT’s Traffic Management System database was approved. The data from the system is being extracted to be used for simulation model development.

MILESTONES ACCOMPLISHMENTS AND DATES: A Fire Events in Tunnel module completed. A conference paper was published, and another was submitted on the bases of the module.

PLANNED ACTIVITIES: The research team plan to collaborate with an industry partner to enable collection of critical tunnel operation data through an automated procedure through the CTMS system used by CDOT (traditionally most of the CDOT critical tunnel operation data was collected manually on paper, while CTMS system was introduced a few years ago to automate traffic interruption event logging). The research team planned to conduct a survey study with DOT tunnel owners to identify the current status of operation data collection for tunnels. The researchers will focus on developing probabilistic framework for tunnel functionality loss analysis in the next reporting period.

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


SUMMARY: Tunneling in fractured rocks must address uncertainties in a rock mass quality measure due to the inherently heterogeneous nature of the rock mass. Traditional deterministic methods for the assessment of rock mass quality are not based upon a complete understanding of these inherent uncertainties, which can result in adverse impact on overall tunnel performance. To address this problem, a Monte Carlo simulation (MCS)-based uncertainty analysis framework is proposed to probabilistically quantify the uncertainties in the Q-system of rock mass classification for tunneling. The main objectives of this project are: 1) Establish a probabilistic Q prediction model based on the Q-log results from the general and location-specific exploration based on a probability distribution function (PDF) of Q-value along the tunnel alignment and the corresponding PDF of support design based on Q-based support chart. 2) Compare prediction results of Q-value using the proposed method and other previous approaches with the actual Q-value on site for validation purpose and conduct sensitivity analysis to evaluate the
robustness of the proposed model. 3) Validate the relationship between site-specific monitored deformation data and actual Q/Span and compare it with Q/Span-deformation relationship.

PROJECT STATUS: This project is now completed, and PhD student Hui Lu successfully defended his PhD dissertation.

MILESTONES ACCOMPLISHMENTS AND DATES: One journal paper has been published and two more are in review. A final project report was completed and was posted in our dissemination site in Zenodo. The techniques developed in the study is being used in the engineering feasibility study of the Eisenhower-Johnson Memorial Tunnel (EJMT).

PLANNED ACTIVITIES: The final project report will be submitted in different DOT archival sites.

PROJECT PERSONNEL: 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 with considerable 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 understand better the causes leading to squeezing ground phenomena. The objectives are to: 1) identify the major causes of squeezing in soft rock; 2) quantifying the squeezing rates and amounts; and 3) 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, along with the miniature tunnel boring machine (TBM), is now fully operational in the laboratory, and the analog rock materials (mixtures of clay and cement) as rock-like materials is developed and characterized to determine physical, mechanical and viscous properties. Several experiments have successfully been conducted on cubical rock specimens including one with a ‘wished-in-place’ lined tunnel, one with TBM excavated tunnel in an anisotropic stress-state and four with TBM excavated tunnel in isotropic 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; 2) selection of rock-like materials for batching and mixing to simulate the rock formation; 3) design and fabrication of a tunnel boring machine for excavating rock specimens while subjected to the true-triaxial state of stress; 4) successful simulation of tunnel excavation and squeezing conditions in laboratory environment under isotropic and anisotropic state of stress; and 5) development of a visco-elastic-plastic constitutive model for the synthetic mudstone specimen through creep tests. Two journal papers have been submitted and are under review. A third journal paper is under development.

PLANNED ACTIVITIES: Research plan for this year onward will be to analyze the collected experimental data from laboratory simulations and develop an experimentally verified squeezing criterion for application in tunnels under squeezing ground conditions.

PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Reza Hedayat and Ph.D. student Ketan Arora

Research at California State University Los Angeles

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

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

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

MILESTONES ACCOMPLISHMENTS AND DATES: Objective I: Phase I completed in March 2018, Phase II completed in summer 2018, and Phase III is in progress. Objective II started in Fall 2018. Two initial predictive models have been developed for predicting the TBM state and detecting anomalies.

PLANNED ACTIVITIES: 1) Including a wide range of anomaly and adverse events for the predictive model; 2) Developing methods based on more complex deep learning models to account for more data elements and achieve higher accuracy levels; 3) Large-scale UTI data collection, exploration, pre-processing for the purpose of adverse event; 4) Building various predictive models based on combination of supervised and unsupervised machine learning techniques to achieve greater accuracy; (5) Enhancing data visualization; (6) Applying the proposed methods on other datasets; (7) Disseminating results.

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

TITLE OF THE PROJECT: Resilience and Sustainability of Underground Transportation Infrastructure

SUMMARY: The goal of this study is to assess to what extent existing guidance for sustainable and resilient infrastructure design is appropriate for use with UTI. Based on this assessment, recommendations will be made for subsequent enhancements. The outcomes of this project will facilitate evaluation of UTI projects for resisting natural disasters, adapting infrastructure to the effects of climate change, and satisfying the various requirements of sustainability (environmental, social, and economic). This goal is in line with the objectives of the UTC-UTI and the broader goal of “Improving the durability and extending the life of transportation infrastructure” set by US DOT.

PROJECT STATUS: The following tasks have been completed: 1) 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; 2) an assessment of subway assets vulnerable to storm surge and sea level rise using the Climate Change & Extreme Weather Vulnerability Assessment and Scoring Tool (VAST) developed by the Federal Highway Administration; and 3) an assessment of the ISI Envision Rating System for a representative UTI project.

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

PLANNED ACTIVITIES: The current ongoing activity is assessing the applicability of the LA Metro Resiliency Indicator Framework for UTI. This task will end the review and assessment of existing frameworks. Following this, the recommendations will be developed.

PROJECT PERSONNEL: Dr. Tonatiuh Rodriguez-Nikl (PI), Dr. Mehran Mazari, new graduate student TBD.


SUMMARY: Structural monitoring of the inner walls of a tunnel is important for safety, performance, liability, and cost. The goal of this project is to develop a fully automated system to perform continuous
monitoring of tunnels during and after construction. The following aspects of this problem require further study:
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, 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 flashlights in 2018. The convolutional neural network (CNN) was trained based on the acquired image database achieving a 97.8% accuracy in automated detection of cracks and other blemishes. Acquired images need to be tagged with location information within the tunnel. Multiple approaches were studied for localization within tunnels and other underground infrastructure in the absence of any GPS, WiFi or any other beacon signal which may be used to define reference locations. We studied a promising approach for indoor localization using stereo cameras named visual Simultaneous Localization and Mapping (SLAM). The relevant systems were designed, developed and implemented in hardware and software using massively parallel Graphic Processing Units (GPU) from NVIDIA (Jetson TX2) and ZED stereo camera.

**MILESTONES ACCOMPLISHMENTS AND DATES:** Prototypes for crack detection were developed in 2017 and 2918. The Visual SLAM system was designed, developed, implemented and tested in both the 3rd floor of the Engineering building and in the field at the Griffith Park Tunnel, verifying functionality and the ability to provide real-time accurate relative localization in underground transportation infrastructure in absence of GPS or any other augmentation signal or system.

**PLANNED ACTIVITIES:** Continuation of the efforts in design and development of an inertial navigation system; system integration of the localization and data acquisition sub-systems for complete autonomous operation; exploration of design, development and implementation of autonomous electrified platforms for application to infrastructure monitoring.

**PROJECT PERSONNEL:** Dr. Fred Daneshgaran, Dr. Marina Mondin, graduate students Antonio Marangi, Nicola Bruno and Fausto Lizzio from Politecnico Di Tornio, Turin, Italy (Visiting scholars at CSULA, all pursuing MS in Mechatronics).

**TITLE OF THE PROJECT:** Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Applications

**SUMMARY:** Self-Consolidating Concrete (SCC), also known as self-compacting concrete, is a type of hydraulic cement concrete that easily forms around the reinforcement without segregation. Design of an SCC mix is chosen based on either powder-type, viscosity modifying admixture-type, or a mixture of the two types depending on structural and constructional conditions, and material available. Due to the improved fresh properties of SCC, this concrete type is more favorable for precast sections that could be used in transportation infrastructure applications. The main objective of this study is to investigate the effect of fiber-reinforcement on fresh and hardened properties of the SCC. The fiber type and content in the SCC mix, affect the compressive strength, tensile strength and crack initiation and propagation. The improved mechanical properties of the fiber-reinforced SCC make it an alternative solution for pre-cast sections for transportation infrastructure applications compared to the conventional concrete. The other objectives of the research are: 1) review of literature to study the application of self-consolidating concrete for underground infrastructures, 2) evaluating fresh and hardened properties of self-consolidating concrete, 3) evaluating the use of recycled fibers to improve the properties of self-
consolidating concrete, 4) investigating the use of sustainable materials (i.e. fly ash and slag) to reduce
the amount of cementitious materials in self-consolidating concrete, and 5) evaluating the crack initiation
and propagation related to properties of the self-consolidating concrete.

PROJECT STATUS: The project is in Phase II. Three sources of recycled fibers were identified and are being
used in the mixture of SCC laboratory samples. Fiber-reinforced SCC beam samples are being prepared
and evaluated for flexural strength. Fresh and hardened properties of fiber-reinforced SCCs are also being
evaluated. Drying shrinkage and water absorption of SCC samples are being evaluated.

MILESTONES ACCOMPLISHMENTS AND DATES: Four papers from this project were submitted to
Transportation Research Board annual meeting and ASCE conferences.

PLANNED ACTIVITIES: The laboratory testing and evaluation, as well as development of database and
analytical models, will continue. Bulk resistivity tests are planned to be performed on fiber-reinforced SCC
samples. Beam samples are being cured and will be evaluated for the flexural strength. The potential
collaborations with DOT and other industry partners are planned.

PROJECT PERSONNEL: Dr. Mehran Mazari, Dr. Tonatiuh Rodriguez-Nikl (co-PI), Keyur Dhawan (MS CE
student), Siavash F. Aval (Research Associate).

Research at Lehigh University

TITLE OF THE PROJECT: Assessing and Improving the Resilience of Highway and Rail Tunnels to Blast and
Fire

SUMMARY: The project team is developing a new framework for evaluating the vulnerability of tunnel
infrastructure to blast and fire hazards. Blast and fire are evaluated as separate hazards as well as
cascading hazards (e.g. a fire following an intentional explosive detonation, or the deflagration of a fuel
tanker due to an initial small fire) where appropriate. The resulting assessments can be used to prioritize
tailor mitigation strategies, systems, and placement to maximize risk reduction with available
resources. The framework leverages several fast running analysis techniques for analyzing the effects of
blast and fire on large structural systems – due to their computational efficiency, these methodologies
can be used to evaluate the effects of blast and fire at a range of locations in large tunnels or among
inventories of tunnels via large batches of simulations using randomly selected inputs. This effort is
computationally focused, and funds dedicated to this project are used primarily for student support.

PROJECT STATUS: Computational efforts focused on blast effects have resulted in the creation of a
conservative method of predicting spall and breach of a concrete tunnel lining from a vehicle-borne
threat. The model leverages experimental data from accepted blast criteria, and additionally employs
Rhinoceros and Grasshopper for calculation and visualization. The intermediate approach has been
validated against computationally intensive finite element modelling using LS-DYNA for several typical
tunnel prototypes. This work was presented at the Transportation Research Board (TRB) Conference in
Washington, D.C. in January 2018, and published in the Transportation Research Record in September of
2018. In a similar manner, Rhinoceros and Grasshopper have been utilized further to create a visual tool
for calculating thermal demands on a tunnel liner for given fire sizes. Accepted structural fire design
criteria are leveraged in the intermediate modelling process. Again, computationally intensive modelling
with the Fire Dynamics Simulator (FDS) software package is utilized for validation of the intermediate
approach. FDS models are compared against existing experimental work by others for validation of
applicable fire hazard effects in the tunnel environment. This work was presented at the 10th International
Conference for Structures in Fire (SIF18) in Belfast, Northern Ireland in June 2018 as well as the TRB Annual
Meeting in Washington, DC in January 2019. A manuscript was submitted in February 2019 to the Fire
Safety Journal and accepted in September 2019 and published. Ongoing efforts are being focused on
analysis of representative tunnels subject to blast loads using numerical models to examine the resilience
of ancillary structural components of the tunnel such as the false ceiling. A journal publication is being
developed as a result of the effort. Another paper is under development which consists of a
comprehensive probability-based framework to examine the cost/benefit performance of various size vehicle fire hazards.


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

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

TITLE OF THE PROJECT: Development of a Blast and Fire-Resistant Structural Tunnel Liner

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

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

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

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

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

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

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

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

**1.2.2 Student Activities**

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

a) A total of 33 students (21 PhD & MS, and 12 BS) are funded by UTC-UTI. Of which 15 (11 PhD & MS, and 4 BS) are working at CSM, 10 (7 MS and 3 BS) at CSULA, and 8 (3 PhD & MS, and 5 BS) at Lehigh. All graduate students actively worked on their thesis and dissertations and are progressing towards the completion of their degrees. 12 REU (Research Experiences for Undergraduate) students assisted the graduate students in their research. Students participated in all aspects research and outreach of the including design of experiments, computational modeling, data analysis, field surveys, project presentations and report writing. One PhD student at CSM graduated in Spring 2019.

b) PhD student Ashton Krajnovich was awarded a 2019 University Transportation Center Outstanding Student of the Year and 1st Place Winner of the Spring 2020 Underground Construction Association Student Research Competition.

c) PhD student Ketan Arora and his advisors Dr. Marte Gutierrez and Dr. Ahmadreza Hedayat received a Best Paper Award from the 4th International Conference on Tunnel Boring Machines in Difficult Grounds, Golden, CO, November 13-15, 2019.

d) PhD student Gauen Alexander was 3rd Place Winner of the Spring 2020 Underground Construction Association Student Research Competition.

e) UTC-UTI students co-authored papers, and/or participated and made presentations in several conferences including the International Conference on Information Technology in Geo-Engineering; 2020 Annual Meeting of the Transportation Research Board; ADSC Northeast Chapter Fall Meeting; 4th International Conference on Tunnel Boring Machine in Difficult Ground; ASCE Geo-Congress 2020; 2019 Association of Environmental and Engineering Geologists Annual Conference; Cal State LA Research Symposium 2020, Annual Research Symposium at Cal State LA; ASCE International Conference on Sustainable Infrastructure; and the 2019 UTC-UTI Workshop.

f) Approximately 60-80 students each time have participated in UTC-UTI co-sponsored “Underground Lunch and Learn” Seminars. The lectures were given by leading experts, practitioners and researchers in the industry and academe, and provided good venue for interactions between lecturers and students.

g) UTC-UTI students continued their research using different tunneling projects including the Seattle Sound Transit Northlink Project, LA Metro Regional Connector Project, North-East Boundary Tunnel Project in Washington DC, Northgate Link Tunnel Project in Seattle, Washington, and the Anacostia River Tunnel Project in Washington DC.

h) Three graduate students and one undergraduate student were involved in data gathering in connection with the engineering feasibility study of the future extension of the Eisenhower-Johnson Memorial Tunnel (EJMT).

i) A CSM Ph.D. student collaborated with Seequent, developers of the Leapfrog implicit geologic modeling software for automated assessment of geologic model uncertainty. Research done by the student will be implemented in Leapfrog as part of UCT-UTI’s T2 plan.
j) A CSM PhD student continued to collaborate with CDOT on a study of the resilience of transportation tunnels including the Eisenhower-Johnson Memorial Tunnel and the Hanging Lake Tunnel in Colorado.  
k) Four CSULA students were awarded by the FHWA Eisenhower Transportation Fellowship and attended the 2020 TRB Annual Meeting in January 2020.  
l) Two additional CSULA students awarded the TRB Minority Fellowship and attended/presented at the 2020 TRB Annual Meeting.  
m) Lehigh students attended sessions and participated in the Transportation Research Board, Tunnel and Underground Structures Committee Meeting.

1.2.3 Outreach Activities  

a) UTC-UTI offered two free webinars during the last reporting period, and these are on: 1) “Tunnel Response to Blast and Fire” with 102 registrants; and 2) “Intelligent Systems Intelligent Systems for Transportation Tunnel Analysis, Design, and Monitoring” with 130 registrants. Each webinar had three presentations and lasted 1.5 hours. Continuing Education Credits and Professional Degree Hours were offered to participants.  
b) UTC-UTI held Session on Underground Transportation Infrastructure as part of the Tunneling Fundamentals, Practice and Innovations Annual Short Course on October 19, 2019. The session had participation from the industry and the academe.  
c) UTC-UTI co-sponsored the “Underground Lunch and Learn” seminar series related to underground transportation infrastructure. The seminars were widely attended by faculty, researchers and students.  
d) UTC-UTI researchers continued to actively participate in several Technical Committees in AASHTO, ADSC; TRB, ASCE, ARMA and other professional organizations.  
e) Dr. Mooney of CSM has continued to lead the planning of a Teach the Professors Program for Civil Underground for summer 2020. Up to 15 professors from civil engineering programs around the US will: 1) attend the North American Tunneling conference in Nashville in June 2020; 2) assist in underground-driven civil engineering curriculum; and 3) implement the curriculum in their classrooms during fall 2020 and spring 2021.  
f) Collaboration between Dr. Wendy Zhu and PhD student Ashton Krajnovich and Seequent has continued to enable the research project and transfer the ideas of uncertainty assessment into the industry.  
g) Lehigh faculty and PhD student Guo participated in a FHWA-sponsored Workshop on Fixed Firefighting Systems in Highway Tunnels, which was hosted at the WSP office in Washington, DC on January 16-17, 2020 following the TRB annual meeting. The workshop attendees included consultants, tunnel designers and operators, state departments of transportation, and academic researchers. The Lehigh team was an active participant in the meeting, and the attendees expressed significant interest in the fast-running fire assessment framework.  
h) Prof. Quiel and PhD students Carlton and Guo attended the Fall Meeting of the Northeast Chapter of the International Association of Foundation Drilling (ADSC) in Bethlehem, PA in November 2019. The PhD students each delivered a 20-minute presentation of their research progress, and the team made valuable contacts with shotcrete installers for future fabrication of experimental specimens.  
i) The Lehigh team has engaged both the Pennsylvania Department of Transportation (PennDOT) and industry representatives at Gannett Fleming for activities related to their project 1 for Year 4. Feedback on the research results and direction has been solicited via regular email communication as well as two conference calls (in October 2019 and January 2020).

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

a) CDOT has provided help from project personnel and extensive data on the daily operation and maintenance of the Eisenhower-Johnson Memorial Tunnel (EJMT) and Hanging Lake Tunnel along I-70 in connection with UTC-UTI’s research on the operational resilience of tunnels. The project team continued to meet and discuss with the CDOT tunnel office on the potential to further mine and enhance CDOT’s CTMS (Colorado Transportation Management Software) database.

b) CDOT has provided $100,000, project personnel and extensive historical data on the geological studies, design and construction of the EJMT as part CSM UTC-UTI’s engineering feasibility study of the future extension of EJMT.

c) Lehigh University was awarded $40,000 from the Pennsylvania Infrastructure Technology Alliance (PITA.org) to leverage UTC-UTI funds in collaboration with Pennsylvania Department of Transportation toward the investigation of fire effects on various tunnel liner surfaces. This award will expand the scope of Task 1 in Year 4.

d) CSULA, CSM and Lehigh were recently awarded a $476,000 NSF-REU award for three years focusing on the research experiences for undergraduate students related to underground transportation infrastructure.

e) Seequent provided licenses for software in support of UTC-UTI’s research on “Adaptive, Predictive 3D Geologic Modeling for Hard Rock Tunneling.” PhD student Ashton Krajnovich is working with Seequent in the computer implementation of his geologic model.

f) Maptek provided several free licenses for their PointStudio and Vulcan software to be used by UTC-UTI students for their studies and research.

g) Skanska-Traylor Bros. provided access to the LA Regional Transit Connector Project. Jay Dee Contractors provided in-kind support valued for the Seattle Northlink Extension Project analysis. Lane Construction company is providing access to Northeast Boundary Tunnel (NEBT) in Washington DC to UTC-UTI’s research on “Data-Driven Risk Mitigation of Cross Passage and Cavern Deformation.”

h) Tongji University in China provided valuable data on: 1) the construction of MuZhai Ling Tunnel in China, and extensive data on the operation and maintenance of Subway Tunnels in Shanghai, China; and 2) TBM construction for the Water Conveyance Project at Jilin Province, China from the China Railway Engineering Equipment Group Co., Ltd.

i) RAMAX LLC has provided free use of their waterjet laboratory, equipment and staff. The estimated cost of $50,000 is provided as cost match to a research project funded by UTC-UTI.

j) CSM IET Waterjet Foundation has provided more than $5,000 support for travel of UTC-UTI researchers and students.

k) CSULA have leveraged the UTC-UTI funds to design, develop, and construct a gantry 3D concrete printer in collaboration with Senior Design Program and Department of Mechanical Engineering at Cal State LA. The large-scale 3D printer will be employed for the project titled “Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Applications.”

l) A recent collaboration started between CSULA and Rensselaer Polytechnic Institute (RPI) in Troy, NY, focusing on the extended application of recycled fibers in Self-Consolidating Concrete. Dr. Tonatiuh Rodriguez-Nikl is working with Dr. Mehran Mazari and Dr. Mohammad Pourhomayoun to facilitate this potential collaboration and graduate student exchange between the two institutes.

m) UTC-UTI funds were leveraged by CSULA to develop and implement Artificial Intelligence algorithms for automatic pattern classification and autonomous indoor navigation technology. These advancements have led to applications in autonomous robotics and systems being developed by a startup company founded by Dr. Fred Daneshgaran and an EX Electrical Engineering student of his who now holds a leading position in Electrified Vehicle's industry.
1.2.5 Faculty and Researcher Accomplishments

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

a) Dr. Marte Gutierrez, UTC-UTI Director, received the Tenth Anniversary Excellent Editorial Board Member Award from the Journal of Rock Mechanics and Geotechnical Engineering. He was Keynote Lecturer at the 3rd International Conference on Information Technology in Geo-Engineering, Guimarães, Portugal, September 29 to October 3, 2019. He also gave Invited Lectures at three different universities and served in the organizing committee of two international conferences.

b) Dr. Mike Mooney, UTC-UTI Associate Director, was awarded the 2019 Tan Swan Beng Endowed Visiting Professorship from Nanyang Technical University (NTU) in Singapore. He spent December 2019 working with NTU colleagues on UTC-UTI research and delivered a public lecture. He was Keynote Lecturer at the International Conference on Case Histories and Soil Properties, Singapore and an Invited Lecturer at the Cold-Water Tunnels Workshop, Copenhagen, Denmark. He also gave a presentation at the Geophysical Aspects of Smart Cities Workshop, Singapore.

c) Dr. Tonatiuh Rodriguez-Nikl was invited to speak at the Engineering the Anthropocene Talk Series at Rensselaer Polytechnic University, Feb 2020. He was member of the American Concrete Institute (ACI) Committee 130 which issued a report on the “Role of Materials in Sustainable Concrete Construction.”

d) Dr. Mehran Mazari was appointed as the Handling Editor for the Transportation Research Record (TRR).

e) Dr. Reza Hedayat delivered a lecture on Sprayed Concrete for Underground Construction at Tongji University, Shanghai, on November 26, 2019.

f) From February 2019 to February 2020, Dr. Hugh Miller has served as the President of the Society for Mining, Metallurgy and Exploration (SME), which serves and represents the Underground Construction Association (UCA) Division of SME. Dr. Hugh Miller also gave invited talks and keynote lectures in six conferences and organized two short courses.

g) Dr. Clay Naito at Lehigh University accepted or published six journal papers, three conference papers, four reports and gave two presentations between October 2019 and March 2020.

h) Dr. Spencer Quiel at Lehigh University accepted or published eight journal papers, three conference papers and delivered two presentations between October 2019 and March 2020.

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. Copies of UTC-UTI publications, reports and presentations are posted at: https://zenodo.org/communities/utc-uti/.

Project Reports

Presentations:
UTC-UTI organized a session on Underground Transportation Infrastructure as part of CSM’s Tunneling Fundamentals, Practice and Innovations Annual Short Course on October 17, 2019 and two webinars.
Selected Journal Publications:


Selected Conference Papers and Presentations and Other Non-Journal Publications:


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

The UTC-UTI website, which is continuously being updated, can be found at: http://underground.mines.edu/utc-uti. Archiving and dissemination are hosted by Zenodo at: https://zenodo.org/communities/utc-uti/. Copies of the Program Progress Performance Reports (or Semi-Annual Project Reports), meeting presentation slides, publications and technical reports from UTC-UTI can be downloaded from this site. Since the launch of the Zenodo archiving and dissemination cite, UTC-UTI reports and publications have been viewed viewed 693 times and downloaded 1670 times..

2.3 Technologies or techniques

Several technologies and techniques are currently in development including: data-driven back-analysis procedures; functional reliability of tunnels during operation; probabilistic methods for rock mass classification and tunnel design; scaled modeling of tunnel squeezing; using DC resistivity to image ahead of tunnel excavations; applications of Data Science, Big Data Analytics, Machine Learning and AI construction and maintenance of UTIs; continuous automatic detection of cracks in tunnels; use of recycled materials; establishing resilience and sustainability metrics for UTIs; improving resilience of UTIs to extreme events of fire and blasts, and through the use of resistant materials; development of adaptive and predictive 3D geologic models; use of InSAR to monitor ground surface deformations above underground excavations; shotcrete removal by waterjet; and new tunnel excavation methods including use of microwave. Specific technological developments include: 1) Development of an input-based, uncertainty assessment technique designed for 3D geologic modeling of fault zones intersecting mountain tunnels, undertaken as a collaborative effort between the researchers and Seequent. 2) In terms of resilience of UTIs to extreme events of fire and blasts, rapid fire and blast assessment tools were developed using Rhino/Grasshopper visual programing platform. Preliminary discussions were carried out with Thornton Tomasetti in Philadelphia to examine utilization in industry evaluation efforts.

2.4 Inventions, patent applications, and/or licenses

Nothing to report for the reporting period.

2.5 Other products

Nothing to report for the reporting period.

3. PARTICIPANTS AND COLLABORATING ORGANIZATIONS

3.1 Organizations which have been involved with UTC-UTI

a) Representatives from the following organizations are members of the UTC-UTI Advisory Board: 1) Colorado DOT (Denver, CO); 2) Federal Highway Administration (Washington, DC); 3) Mott MacDonald (Millburn, NJ); 4) Council of University Transportation Centers (Washington, DC); 5) Arup (New York, NY); 6) Penn DOT (Harrisburg, PA); 7) WSP/Parsons Brinckerhof (Chicago, IL, Washington DC, New York, NY); and 8) Tongji University (Shanghai, China).

b) The following organizations have provided cash, in-kind cost-match and other support 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) Lane Corporation (Washington, DC); 11) Pennsylvania Infrastructure Technology Alliance (Pittsburgh, PA); 12) California State University Transportation Consortium (San Jose, CA); 13) Seequent (Christchurch, New Zealand); 14) Colorado Geological Survey (Golden, CO); 15)
Representatives from the following organizations have given presentations in the UTC-UTI co-sponsored seminar series: Geosyntec Consultants (Atlanta, GA); JayDee Contractors (Sommerville, MA); Queen’s University (Ontario, Canada); Kiewitt-Shea Contractors (Newburgh, NY); Traylor Brothers (Bethesda, MD); HECLA Mining Company (Coeur D'alene, ID), WSP (New York, NY).

3.2 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. Software companies have provided free software licenses in support of UTC-UTI research efforts.

4. IMPACT

4.1 What is the impact on the development of the principal discipline(s) of the program?
The main research focus of UTC-UTI is the development and deployment of major improvements in the design, planning, construction, maintenance, operation, retrofit and expansion of underground transportation infrastructure to make them more durable and to extend their lifetime. These developments will be realized by moving away from largely empirical and tradition-based procedures to an intelligent and data-driven system that uses recent progress in condition monitoring, sensing and asset/performance assessment, as well as in new construction materials and technologies. Underground transportation projects require large budgets and long construction times. It is important to develop advanced technologies that will improve the durability and extend the life of underground transportation infrastructures to ensure that they function as intended, 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 33 students and three postdocs were supported by UTC-UTI through 17 research projects. UTC-UTI also continued to hold outreach and recruiting initiatives aimed at encouraging K-12 and undergraduate students to pursue advanced degrees in STEM.

4.4 What is the impact on physical, institutional, and information resources at the university or other partner institutions?
Results from UTC-UTI are being widely disseminated and archived for long-term access using Zenodo, which is a publicly available data repository. Archived research results can help support future research
in the area of Underground Transportation Infrastructure at partner institutions and the academe in general, and to promote technology transfer to the industry. Links to the archived results are actively promoted through our Center webpages including our archiving webpage in Zenodo.

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

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

b) Sharing of innovations via continuing education (including short courses), seminars (including webinars) and workshops. Examples are given above. Other examples of direct technology transfer: i) implementation of research results in Seequent’s Leapfrog computer program, and ii) contributing towards the setting up of a startup company for autonomous robotics and systems.

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

d) Dissemination through publications of research in journals and conference proceedings, reports, and design manuals. All UTC-UTI output are also disseminated through our archiving and dissemination website at Zenodo where they have been viewed 693 times and downloaded 1670 times.

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

5. CHANGES/PROBLEMS
Nothing to report.

\(^1\) No direct or indirect DOT funds were used for international activities and travels.