Semi Annual Progress Report #4
Submitted to

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

Federal Grant number: 69A3551747118

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

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

October 31, 2020

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

Recipient Organization: Colorado School of Mines, 1500 Illinois St., Golden, CO 80401
Project/Grant Period: November 2016 – September 2022
Reporting Period: April 1, 2010 – October 31, 2020
Report Frequency: Semi-annual

Signature: [Signature]
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

PROJECT TITLE: 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 were 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 complete (see prior report). (Obj. 2) The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is complete and 3D finite element...
modeling is complete. (Obj. 3) The analysis of LA Regional Connector SEM cavern measured data is complete. The back-analysis procedure to identify ground properties using computational simulation and surrogate modeling methods is developed.

MILESTONES ACCOMPLISHMENTS AND DATES: PhD student Tamir Epel completed the liner loading and cross passage study and final project report. PhD student Haotian Zheng has completed his work.

PLANNED ACTIVITIES: The project is complete.

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

PROJECT TITLE: 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.


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.

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

SUMMARY: In December of 2013, Big Bertha broke down approximately 300 m from where it started, requiring major repairs for which a 37m deep shaft was constructed in the fall of 2014. Gaining access to the TBM required significant dewatering at multiple depths ranging from near surface to greater than 60m. Dewatering continued through February 2015, resulting in a 750m by 500m elliptical patch of subsidence with a maximum value of 3.5 cm measured near its center. We are using three separate
Sentinel-1 InSAR datasets to verify the location of previously reported subsidence, as well as measure the quantity and spatial extent of post-subsidence rebound.

**PROJECT STATUS:** The current project started in January 2019. All three datasets have been downloaded and 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

**PROJECT TITLE:** Characterization, Analysis and Prediction of Tunnel-Induced Ground Surface Settlement Using Machine Learning Methods and InSAR Imagery Analysis

**SUMMARY:** During excavation and stabilization of tunnels using supports, changes in the stress state and loss of ground support occur in the groundmass surrounding the excavation. These changes are often manifested in the form of settlement at the ground surface, particularly for shallow tunnels. For urban tunnel constructions, the ground settlement should be limited within a tolerable threshold to prevent damage to aboveground structures. Therefore, characterizations, analyses, and predictions of the ground movement are of vital importance both in the tunnel design and construction planning stages. The objectives of this project are: 1) characterize the tunnel-induced settlements using Interferometric Synthetic Aperture Radar (InSAR) imageries and ground monitoring data; 2) analyze possible influences on structures; and 3) and predict tunnel-induced ground deformations using machine learning methods. Specifically, this project aims to propose an integrated remote sensing approach combining InSAR imagery and machine learning methods to study tunnel-induced deformation and corresponding possible influence on aboveground structures.

**PROJECT STATUS:** This project, started in September 2019, has completed one objective and partially completed the second project. (1) For the prediction of tunnel-induced ground settlements, this project has proposed a deep learning technique named KPBNN model, which is an integration of Kernel Principal Component Analysis (KPCA), Particle Swarm Optimization (PSO), and Back-Propagation Neural Network (BPNN). Additionally, a quantile error (QE) criterion is proposed to assess the model performance with the consideration of that underpredictions may cause project failure and even loss of lives, unacceptable in a real tunneling project. One manuscript was submitted to a peer-reviewed journal and is currently under review. (2) For characterization and analysis of tunnel-Induces settlements, datasets have been downloaded. InSAR time-series analysis has been conducted using a small-baseline method.

**MILESTONES ACCOMPLISHMENTS AND DATES:** 1) Completed data collection and KPBNN model algorithm script for predicting tunnel-induced ground settlements (May 2020); 2) One completed and submitted paper entitled “Predictions of tunneling-induced ground settlements using an improved back-propagation neural network model”; and 3) Downloaded InSAR data and processed time-series analysis.

**PLANNED ACTIVITIES:** 1) Collect monitoring settlement data of aboveground structures in Los Angeles; 2) characterize tunnel-induced settlements according to the InSAR datasets; and 3) analyze tunnel-induced
ground settlements and their possible influences on aboveground structures via a combination of InSAR time-series analysis and machine learning methods.

**PROJECT PERSONNEL:** Dr. Wendy Zhou, Dr. Marte Gutierrez, and PhD student Linan Liu

**PROJECT TITLE:** Functional Reliability of Tunnels and Its Impact on Transportation Network Resilience

**SUMMARY:** Tunnels are typically one of the most critical links in a transportation network and they greatly undermine network resilience when they lose functionality (either entirely or partially) due to hazardous loading conditions. Closure or limited access of traffic tunnels (function loss) is very costly and has great negative impacts on the public. Each tunnel owner or manager typically analyzed these events in a case-by-case basis. There is currently a lack of systematic data collected or analysis done to investigate the overall trend for the occurrence and severity of such events. A systematic analysis of tunnel function-loss cases can answer some of the most critical questions of interest to tunnel owners. This project aims at developing two fundamental elements to enable this analysis, namely 1) a tunnel operation data collection framework that can be adopted for critical tunnels across the country, and 2) a probabilistic framework for quantifying tunnel resilience (functionality loss) as conditional distribution of hazard type and intensity. The project team will work closely with local DOT to implement some of the developed models and tools with the vision to expand the application of the research outcome nationwide.

**PROJECT STATUS:** This project started in August 2017. Since April 1st, 2020, stochastic simulation model was developed to estimate the resilience of the tunnel. The maintenance and operation modules were developed to account for these events in the simulation model. The data collection framework was finalized, and journal paper describing it was submitted. Next, modules of the disruptive events for the simulation model was combined. The model was validated for Eisenhower Johnson Memorial Tunnel whose data was obtained from CDOT. The simulation model was explained in the second journal paper. To check the applicability of the simulation model, data was collected from National Tunnel Inventory for twenty-two tunnels and analysis was performed. The sensitivity analysis of the simulation model was also performed to check the criticality of different modules and its sensitivity towards various parameters.

**MILESTONES ACCOMPLISHMENTS AND DATES:** Data framework was completed and journal paper explaining this framework is submitted. The simulation model with all the modules was completed and another journal paper was submitted describing it.

**PLANNED ACTIVITIES:** Third journal paper illustrating the applicability of the simulation model for other tunnels along with the sensitivity analysis for various events will be submitted.

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

**PROJECT TITLE:** 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 can help improve geologic understanding and 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 before installing 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. Following excavation, the calibrated geologic model can inform potential expansions in the vicinity of the existing tunnel alignment. The model discrepancy is used to formulate and assess subsurface geology predictions in the context of a 3D geologic model. Bayesian statistics provide a convenient framework for validating and updating subsurface geology predictions 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. As of September 2020, Objective (1) is 100% complete, and Objective (2) is 50% complete. The robust workflow for geologic model uncertainty assessment developed for Objective (1) is being leveraged to assess the uncertainty about fault zones intersecting the Eisenhower-Johnson Memorial Tunnels in Colorado, USA. The methodology for completing Objective (2) is complete, and testing has begun on dynamic model updating.

**MILESTONES ACCOMPLISHMENTS AND DATES:** A peer-reviewed journal article on geologic model uncertainty assessment was published in Solid Earth, and two peer-reviewed conference papers were published to ARMA 2020 and WTC 2020. (2) Collaboration with Seequent has led to the development of a proprietary Beta build of Leapfrog Geo, enabling the researchers to freely and rapidly generate uncertainty assessments of geologic models.

**PLANNED ACTIVITIES:** Two manuscripts for peer-reviewed journals are being written. The first manuscript builds on Objective (1), exploring the use of Bayesian inference for model updating based on tertiary information collected during tunnel excavation. The second manuscript is being expanded from the conference paper published in ARMA 2020, focusing on analyzing rock mass structure based on point cloud data. Thesis defense and UTC-UTI report delivery are planned to be completed in January 2021.

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

---

**PROJECT TITLE:** 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 (a) identify the major causes of squeezing in soft rock; (b) quantifying the squeezing rates and amounts: and (c) develop experimentally verified squeezing criterion for broader application to tunnels. To achieve the research objectives, a series of novel true-triaxial compression experiments with simultaneous tunneling in rock has been conducted.

**PROJECT STATUS:** This project was started in August 2017 and has focused on developing the experimental setup for conducting the true-triaxial simulation experiments. A physical model test setup having triaxial cell and the miniature tunnel boring machine (TBM) was designed and fabricated. The synthetic mudstone (mixtures of clay and cement) analogous to natural mudstone was developed and characterized to determine physical properties and mechanical behavior. Several experiments were successfully conducted on a cubical rock specimen including one with a ‘wished-in-place’ supported tunnel, one with TBM excavated tunnel in anisotropic stress-state, and several TBM excavated supported and unsupported tunnel in isotropic stress-state state to study the time-dependent convergence of the tunnel cross-section. A criterion to determine the convergence of supported as well as unsupported tunnel has been proposed based on the experimental observations.

**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. One journal paper has been published and three journal papers have been submitted and are under review.

**PLANNED ACTIVITIES:** All research objectives have been achieved and the project is now completed.

**PROJECT PERSONNEL:** Dr. Marte Gutierrez, Dr. Reza Hedayat and Ph.D. student Ketan Arora
PROJECT TITLE: The Applications of Data Science and Big Data Analytics in Underground Transportation Infrastructure

SUMMARY: This research project focuses on the applications of data science, machine learning, 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 and Artificial Intelligence (AI) techniques to predict the TBM state and status in real-time as well as future adverse events in UTI such as structural defects and anomalies.

PROJECT STATUS: Objective I: We are refining the predictive model and developing new techniques to improve results. We used a big dataset from Seattle Northlink 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. Objective II: We have developed a predictive model that can predict the status of TBM and its performance in real-time. We have trained and tested this model on big dataset from LA METRO and are developing algorithms to improve the accuracy of this model. We are also working on algorithms to predict the future structural defects using deep neural networks.

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 Net is effective and accurate in predicting the composition of soil and specifications of ground. Objective II has started in Fall 2018. Two initial predictive models have been developed so far for predicting TBM state/performance and anomaly detection. The research is still in progress. New research goals added to the project in Summer 2020. The results have been presented in TRB 2020, and also published in a journal in July 2020.

PLANNED ACTIVITIES: (1) Developing new data-driven and AI-based algorithms for predicting/detecting structural defects; (2) Defining and including a wide range of anomaly and adverse events for our predictive model; (3) Developing new methods based on more complex deep learning models that can take into account more data elements to achieve higher accuracy levels; (4) Building various predictive models based on combination of supervised and unsupervised machine learning techniques to achieve even higher accuracy; (5) Adding more data visualization; (6) Developing, training, and applying the proposed methods on other datasets; (7) Publishing/presenting more conference/journal papers.

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

PROJECT TITLE: Resilience and Sustainability of Underground Transportation Infrastructure

SUMMARY: The goal of this study was 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 can be made for subsequent enhancements. 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. The project is finished, and final report is complete.

**MILESTONES ACCOMPLISHMENTS AND DATES:** The vulnerability assessment of underground assets using the VAST tool is published and was presented at the 2018 International Conference on Transportation and Development (July 2018). The literature review and the assessment of Envision are complete and were published and presented at the 2019 International Conference for Sustainable Infrastructure. The final report was competed in July 2020.

**PROJECT PERSONNEL:** Tonatiuh Rodriguez-Nikl (PI), Mehran Mazari (co-PI)

**PROJECT TITLE:** 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 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. We address investigation and development of (a) techniques for data acquisition (reliable, cost efficient, and easily automated); (b) techniques for communication to the processing center; (c) techniques for post processing of data for detection algorithms; (d) algorithms and techniques for pattern detection and classification; (e) software for drawing recommendations from the post-processed data.

**PROJECT STATUS:** We are addressing the challenge of localization of the monitoring instrument inside of tunnels. The current focus is in two directions. The first is integration of Global Navigation Satellite Systems (GNSS) with SLAM for integrated localization indoor and outdoor. The second is use of algorithmic approaches to MultiRobot System (MRS) management and task assignment. We have addressed the first problem, which is requires data fusion of two subsystems: 1) ArduSimple Real-Time Kinematics Differential GNSS (DGNSS) unit has been purchased and tested for functionality; 2) the SLAM technique that has been developed already is being refined. Our design is focused on a mobile module called Rover and a stationary base unit that sends navigation corrections to the Rover. Robot Operating System (ROS) is used as the core integration platform and our R&D is focused on use of Kalman filtering for data fusion. Due to the school closure, we have not been able to conduct live experiments and the study of the algorithms and data fusion techniques has been conducted via simulations. Development of simulation programs for MRS task assignment for management of a coordinated fleet of autonomous platforms for UTI inspection is continuing. Preliminary results are promising.

**MILESTONES ACCOMPLISHMENTS AND DATES:** Vehicle based data acquisition systems (camera and video based) were designed, developed, implemented and tested using commercial off the shelf equipment in years 2017 and 2018. The deep convolutional neural network (CNN) was trained based on the acquired image database achieving 98% accuracy in automated detection of cracks and other blemishes. Acquired images need to be tagged with location information within the tunnel. In 2019, multiple approaches were studied for localization within tunnels and other underground infrastructure in the absence of any GPS, WiFi or any other beacon signal. An indoor localization technique was designed, developed, implemented and tested in 2019. This technique uses stereo cameras and is named visual Simultaneous Localization and Mapping (SLAM). The current focus is on improving the localization techniques as described above.

**PLANNED ACTIVITIES:** Continuation of the efforts in design and development of an integrated GNSS and SLAM system for navigation. Exploration of design, development and implementation of fleet of Autonomous Electrified platforms for application to infrastructure monitoring.
PROJECT PERSONNEL: Fred Daneshgaran (PI), Marina Mondin (co-PI), Aldo Adame and Alejandro T Alvarado (CSLA MSEE students), Matteo Pezzetti (Mechatronics), Andrea Benedetto (CS), and Luca Romanello (Mechatronics), students from Politecnico Di Tornio, Turin, Italy (Visiting scholars at CSLA).

PROJECT TITLE: 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. The 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 the 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 the 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 number 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: We have started the development and optimization of additive manufacturing process of our cementitious mixtures. Several trials samples have been printed in the lab. However, due the campus closure, we have moved our efforts to focus on the simulation of the additive manufacturing process.

MILESTONES ACCOMPLISHMENTS AND DATES: The project report was submitted in spring 2020.

PLANNED ACTIVITIES: We will be continuing with the simulation of additive manufacturing process and studying the effect of mixture rheology on printing properties and the stability of the printed sample.

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

Research at Lehigh University

PROJECT TITLE: Fire Resistance of Tunnel Surfaces

SUMMARY: The research effort is building upon results of UTC-UTI efforts at Lehigh during Years 1 to 3 to explore the impact of surface coating on the thermal resistance of concrete tunnel liners. The research involves a 2-phase effort:

1. The strength degradation of concrete will be assessed through destructive testing. A matrix of concrete mixes will be developed and used to fabricate uncoated reinforced concrete panels. The panels will be exposed to heat profiles comparable to fire events and evaluated for damage via spalling, dehydration, of heat-induced cracking. The effects of moisture content, applied loading, and concrete constitutive properties will be assessed.

2. Similar panels with painted and tiled surfaces will be examined using the same testing approach. These surface coatings are often used in the current tunnel inventory, and their potential for influencing the panel response compared to the results of Phase 1 will be assessed.

Both phases will be accompanied by computational modeling efforts to delve into the root causes of the mechanical and material response of these panels to fire. This task involves both small-scale
experimentation and computational analysis at Lehigh’s ATLSS Laboratory. Funds dedicated to this task will be used for student support as well as the cost of specimen fabrication and testing.

**PROJECT STATUS:** A matrix of experimental specimens has been built using the same base panel design (24”x18”x6” normal weight concrete panels with mild reinforcement) but with the following fire-exposed surface configurations: bare concrete, tiled with material used in a typical US tunnel (procured from a major supplier of tunnel tile), and coated with passive fire resistant paneling (procured from a fire protection products vendor). Specimen instrumentation and preparation was completed in mid-March and concrete casting was delayed until June 2020 due to the shutdown of the ATLSS Laboratory due to the nationwide coronavirus outbreak. Intumescent paints, SFRM, and tile were procured in July 2020. Four bare surface specimens were tested as a baseline control for the test series. A preliminary investigation of residual concrete properties after severe heating was completed. Strength loss estimates were found to be consistent with past literature and is not dependent on specimen geometry.

**MILESTONE ACCOMPLISHMENTS AND DATES:**
3. Awarded supplemental funding to expand the experimental matrix via a Pennsylvania state research program (pitapa.org) – January 2020.
5. Preliminary estimates of behavior based on previous testing – March 2020.
8. Completed residual strength study – September 2020

**PLANNED ACTIVITIES:**
1. Install tile and passive fire protection materials on specimen subsets.
2. Conduct high-temperature testing using the test setup established in previous tasks.
3. Conduct numerical analysis of tested specimens.
4. Develop semi-empirical guidance for the response of coated and bare concrete tunnel liner panels to fire.

**PROJECT PERSONNEL:** Ph.D. student Aerik Carlton (lead student), Ph.D. student Qi Guo, M.Sc. student Ziyan Ouyang, Prof. Spencer Quiel (lead faculty), and Prof. Clay Naito.

**PROJECT TITLE:** Resilience Assessment of Tunnels Exposed to Blast

**SUMMARY:** In Years 1 through 3, researchers at Lehigh University have been developing a new framework for evaluating the vulnerability of tunnel infrastructure to blast and fire hazards. The effort thus far has focused on the spatial and temporal distribution of the loading effects due to blast and fire. Specifically, two journal papers have been submitted (one published and the other with revisions under review) which proposed fast-running and conservatively accurate models which calculate the blast-induced loading as well as fire-induced heat flux exposure for a range of relevant threats. Activities in Year 4 will focus on extending the tool to include structural damage and resulting functionality consequences due to the mapped exposure for blast hazards. In a subproject funded by a Pennsylvania state agency, the PIs have been evaluating false ceiling structures that are commonly installed in tunnels to separate the main shaft from ventilation and other mechanical systems. This year 4 task will leverage those results and consider blast effects on other peripheral systems in addition to examining the tunnel liner (which was the focus of the PIs research in previous years of this project). The resulting assessments will be used to prioritize and tailor mitigation strategies, systems, and placement to maximize risk reduction with available resources. High fidelity modeling and test data (where available in the literature) will be used to validate the fast-running analytical models and identify new research needs. The quantity of damage will be correlated with the potential for progressive structural damage as well as down-time and economic costs. This effort is computationally focused, and funds dedicated to this task will be used primarily for student support.

**PROJECT STATUS:** A comprehensive blast vulnerability assessment has been completed for two prototype tunnels that feature false ceiling structures for ventilation purposes. The assessment included the following: (1) calculation of blast loading for a range of threat sizes via computational fluid dynamic (CFD) modeling, (2) characterization of the blast resistance functions for each ceiling panel type (via both
simplified calculations and nonlinear finite element simulations), (3) damage mapping for each hazard
level, and (4) retrofit strategies to mitigate the risk of collapse following an intentional or accidental blast.
The results of this study were accepted and published in ASCE’s *Journal of Performance of Constructed
Facilities*. This task has successfully leveraged the results of the Pennsylvania-funded subproject to deliver
damage mapping approach to evaluating the collapse potential of false ceiling tunnel structures based
on a realistic distribution of blast load effects. As requested by AASHTO T20 committee, scope was pivoted
from examination of other peripheral components under blast to examination of the vulnerability of false
ceiling structures to fire events. Numerical analysis and evaluation structural consequences for a range of
fire hazards was conducted and a publication was submitted to the TRR.

**MILESTONES, ACCOMPLISHMENTS AND DATES:**

2. Acquisition of drawings to develop prototype tunnels with false ceilings – June 2019.
3. CFD modeling to obtain spatial and temporal blast load distributions in two prototype tunnels – October 2019.
5. Vulnerability assessment via damage mapping performed for as-built conditions – November 2019.
8. Numerical evaluation and manuscript submission on fire resilience of drop ceiling systems – August 2020.

**PLANNED ACTIVITIES:**

1. Present the results of the fire study at TRB in January 2021.
2. Present the results of the blast study at ICPS6 in May 2021.
3. Examine vulnerability of drop ceilings to cascading events of blast following fire events.

**PROJECT PERSONNEL:** M.Sc./Ph.D. student Ziyan Ouyang (lead student), Ph.D. student Aerik Carlton,
(secondary lead), Ph.D. student Qi Guo, Prof. Clay Naito (lead faculty), and Prof. Spencer Quiel.

**PROJECT TITLE:** Interaction of Mechanical Systems with Structurally Significant Fire Events

**SUMMARY:** In Years 1 through 3, the Lehigh team has been developing a new framework for evaluating
the vulnerability of tunnel infrastructure to blast and fire hazards. The effort thus far has focused on the
spatial and temporal distribution of the loading effects due to blast and fire. Specifically, two journal
papers have been submitted (one published and the other with revisions under review) which proposed
fast-running and conservatively accurate models which calculate the blast-induced loading as well as fire-
induced heat flux exposure for a range of relevant threats. To date, the fire-focused tools have been
developed for fire scenarios that have natural ventilation within tunnels with negligible longitudinal grade
and no fixed fire suppression systems. The current framework will be enhanced to consider the effects of
ventilation and grade on the movement of smoke and hot gases. Initial efforts will be made to consider
the influence of fixed fire suppression systems on the growth and intensity of the fire event. The impact
of fire exposure on the integrity of these mechanical systems will also be considered. It is expected that
the consideration of fixed fire suppression will be an ambitious step forward in this methodology and
extend into the Year 5 activities on this project.

**PROJECT STATUS:** The Lehigh team hired a postdoctoral researcher in January 2020 who is partnering with
the PhD students on this effort to integrate ventilation effects into the fire assessment framework that
was developed during prior years of this UTC-funded effort. The postdoc has leveraged his significant
experience in CFD fire modeling to develop validated simulations of large fires that are subjected to critical
velocity ventilation (to prevent back-layering at the fire site). The validated modeling approach will be
used to calibrate new capabilities in the existing fast-running fire assessment framework. A
comprehensive fire vulnerability assessment has been completed for three prototype tunnels that feature
ventilation with no false ceilings. A software application package, written in Matlab and compiled for
wider use, is currently in development to make the fire assessment framework (which will include the
results of this task) accessible to the tunnel engineering community. Information on mechanical systems
used in PennDOT tunnels was acquired and work has initiated on fire resilience assessment of common systems subject to fire events.


**PLANNED ACTIVITIES:** (1) Roll out a completed beta version of the fast-running fire assessment framework for test-use by industry partners. (2) Submit journal publication focused on the newest developments of said framework, focusing on the implementation of ventilation at critical velocity. (3) Present results at the next UTC-UTI symposium to disseminate the newest developments of this framework. (4) Solicit feedback from industrial partners for subsequent development opportunities for the results of this research.

**PROJECT PERSONNEL:** Postdoctoral researcher Zheda Zhu (lead), Ph.D. student Qi Guo (secondary lead), Ph.D. student Aerik Carlton, Prof. Spencer Quiel (lead faculty), and Prof. Clay Naito.

### 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 23 students (21 PhD & MS, and 2 BS) were funded by UTC-UTI. Of which 9 (8 PhD & MS, and 1 BS) were working at CSM, 10 (9 MS and 1 BS) at CSULA, and 3 (PhD & MS) at Lehigh. All graduate students actively worked on their thesis and dissertations and are progressing towards the completion of their degrees. Two 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. Five graduate students graduated during the reporting period (2 at CSM, 2 at CSULA and 1 at Lehigh).


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

d) Three graduate students were involved in data gathering in connection with the engineering feasibility study of the future extension of the **Eisenhower-Johnson Memorial Tunnel (EJMT)**.

e) 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.

f) 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.
g) CSM student Ashton Krajnovich participated in the Seequent Lyceum 2020 as a part of an expert panel named “How can software suppliers support best practice for uncertainty in engineering geology?

h) Lehigh Ph.D. student Zheda Zhu was hired as postdoctoral researcher in January 2020 to lead Task 3 and assist the faculty with documentation and reporting.

i) A CSULA student presented her research in Women in Data Science Conference 2020.

j) CSULA students Presented their research in Cal State LA DIRECT STEM workshop.

k) Four CSULA students selected for Eisenhower Transportation Fellowship attending the TRB Annual Meeting in January 2020.

l) Two CSULA students selected for TRB Minority Fellows Program attending the TRB Annual Meeting in January 2020.

m) Two CSULA graduate students have been working on this project during the reporting period.

n) A team of six CSULA undergraduate students have worked partly supported by the UTC project to develop a Mid-Scale Concrete 3D Printer.

1.2.3 Outreach Activities

a) UTC-UTI offered a free webinar on April 15, 2020 with a theme of “Intelligent Systems for Transportation Tunnel Analysis, Design, and Monitoring” with 130 registrants. The webinar had three presentations and lasted 1.5 hours. Continuing Education Credits and Professional Degree Hours were offered to participants.

b) 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.

c) UTC-UTI researchers continued to actively participate in several Technical Committees in AASHTO, ADSC; TRB, ASCE, ARMA and other professional organizations.

d) Collaboration between Ashton Krajnovich and Seequent Limited has continued to enable the research project and transfer uncertainty assessment ideas into the industry. The partnership recently discussed expansion from the current Leapfrog Geo Beta build into the developing Seequent EVO API, a connected ecosystem of solutions that enable you to work seamlessly across your workflow.

e) Lehigh faculty and PhD student Guo participated in a FHWA-sponsored workshop on fixed fire-fighting 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. This meeting served as a catalyst for advancing the development of the beta version of the framework program. Quiel is serving as technical reviewer for the resulting report.

f) The Lehigh team has engaged both the Pennsylvania Department of Transportation (PennDOT) and industry representatives at Gannett Fleming for activities related to Task 1 for Year 4. Feedback on the research results and direction has been solicited via regular communication.

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) 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.

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

e) 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.”

f) 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.

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

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

i) 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.”

j) 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.

k) 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 18th Distinguished Paper Award from The Society of Powder Technology Japan. He gave an online presentation in the Civil, Environmental and Geodetic
Engineering Seminar Series, Ohio State University, and was interviewed in the Gold Nuggets Series of the Humanitarian Engineering Program, Colorado School of Mines.

b) CSULA faculty Dr. Mohammad Pourhomayoun received new grants from the City of Los Angles and NASA for projects focusing on various applications of AI in Urban Sustainability.

c) UTC-UTI faculty member Professor Clay Naito at Lehigh University accepted or published 7 journal papers, 2 conference papers, and 3 reports April 2020 and September 2020.

d) UTC-UTI faculty member Associate Professor Spencer Quiel at Lehigh University accepted or published 10 journal papers, 2 conference papers, and 2 reports between April 2020 and September 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


Selected Journal Publications:


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


UTC-UTI Semi-Annual Report #4 – October 31, 2020


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. 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 960 times and downloaded 3502 times since the start of the center, and viewed 257 times and downloaded 1832 times in the last reporting period.

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 programming 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) Pennsylvania Department of Transportation (Philadelphia, PA); and 16) Gannett Fleming (Harrisburg, PA).

c) 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 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 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 web page in Zenodo.

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

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

b) Sharing of innovations via continuing education (including short courses), seminars (including webinars) 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
The COVID-19 pandemic has impacted many of the activities and outcomes of UTC-UTI resulting in reduced outreach activities of UTC-UTI, its faculty, researchers and students. Recruitment of new students, particularly from abroad, has also been delayed due to difficulty in obtaining visas to travel to the US. Nevertheless, the Center is on track with its projects, reporting and dissemination.

---

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