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Marte Gutierrez, Ph.D.
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: mgutierr@mines.edu

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University Transportation Center for Underground Transportation Infrastructure (UTC-UTI)

UTC-UTI is a Tier 1 University Transportation Center funded by the U.S. Department of Transportation under the FAST (Fixing America's Surface Transportation) Act. UTC-UTI is devoted to the advancement of Underground Transportation Infrastructure as cost-effective, safe and sustainable solution to increasing demand for conveying people, goods and services particularly in many urban areas in the US. UTC-UTI addresses the FAST Act Research Priority Area: "Improving the Durability and Extending the Life of Transportation Infrastructure." UTC-UTI is a collaborative effort between Colorado School of Mines (CSM), California State University Los Angeles (CSULA) and Lehigh University.

1. ACCOMPLISHMENTS

1.1 Major Goals of the UTC-UTI

The main objectives of UTC-UTI are to:

1. Develop technologies that will improve the durability and extend the life of new and existing UTIs;
2. Educate and train the next generation of UTI engineers and personnel; and
3. Transfer research results and technology to industry.

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

1.2 Progress and Accomplishments

1.2.1 Research Activities

During the reporting period, UTC-UTI funded a total of 14 research projects (7 at CSM, 4 at CSULA and 3 at Lehigh). Highlights of these projects are given below.

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

<u>TITLE OF THE PROJECT:</u> Data-Driven Risk Mitigation of Cross Passage and Cavern Deformation

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

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

project team. (Obj. 2) The evaluation of cross passage monitored data during Seattle Northlink tunnel construction is complete and 3D finite element modeling is 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: Ph.D. student Tamir Epel completed the liner loading and cross passage study and final project report and successfully defended his Ph.D. dissertation in March 2020. Ph.D. student Haotian Zheng is continuing with his research on reliability-based analysis of the cross-passage excavation and expects to finish in May or Summer 2021.
PLANNED ACTIVITIES: The LA Metro study will be completed in the next reporting period. The aim is 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, Ph.D. 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 is used to integrate the knowledge of spatial variability and uncertainty into the planning, design and construction activities in soft ground tunneling projects. The motivation of this research is to characterize the soil transition location uncertainty and characterize occurrence critical subsurface features, such as karstic voids, within tunnel envelope. 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: This project was completed in December 2020. A probabilistic framework has been developed to characterize the soil transition location uncertainty in soft ground tunneling applications. Tunnel boring machine (TBM) data is used to validate the estimates of soil transition location from the probabilistic framework. A probabilistic framework has been developed to characterize the frequency, the number, and the occurrence probability of karstic void frequency within the tunnel envelope.
MILESTONES ACCOMPLISHMENTS AND DATES: Ph.D. student Rajat Gangrade is in the final semester of his research and plans to complete his Ph.D. at the end of Spring 2021.
PLANNED ACTIVITIES: Research plan for this year involves submitting journal articles for the discussed project.
PROJECT PERSONNEL: Dr. Mike Mooney, Dr. Whitney Trainor-Guitton, and Ph.D. student Rajat Gangrade.

TITLE OF THE PROJECT: Mapping Urban Excavation Induced Deformation in 3D via Multiplatform InSAR Time-Series
SUMMARY: Excavation of a subway station and rail crossover cavern in downtown Los Angeles, California, USA induced over 1.8 cm of surface settlement between June 2018 and February 2019 as measured by a ground-based monitoring system. Point measurements above the excavation were extracted from Interferometric Synthetic Aperture Radar (InSAR) time-series analyses using multiple sensors with different wavelengths. These sensors include C-band Sentinel-1, X-band COSMO-SkyMed, and L-band Uninhabited Aerial Vehicle SAR (UAVSAR). The InSAR time-series point measurements were interpolated to continuous distribution surfaces, weighted by distance, and entered in the Minimum-Acceleration

(MinA) algorithm to calculate 3D displacement values. This dataset, composed of satellite and airborne SAR data from X, C, and L band sensors, revealed previously unidentified deformation surrounding the 2nd Street and Broadway Subway Station and the adjacent rail crossover cavern, with maximum vertical and horizontal deformations reaching 2.5 cm and 1.7 cm, respectively. The analysis shows that airborne SAR data with alternative viewing geometries to traditional polar-orbiting SAR satellites can be used to constrain horizontal displacements in the North-South direction while maintaining agreement with ground-based data.

PROJECT STATUS: The current project started in January 2020. Data Processing and algorithm development were completed in November 2020. Figures were developed, and a manuscript was written and submitted to the journal entitled Sensors.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Completed Minimum Acceleration algorithm script for extracting 3D displacement vectors (March 2020), (2) Acquired UAVSAR, Sentinel-1, and Cosmo-SkyMed data that are covering downtown Los Angeles (October 2020), (3) Completed and submitted manuscript to the journal entitled Sensors, and (4) Ph.D. Student Kendall Wnuk successfully defended his Ph.D. dissertation in March 2021.

PLANNED ACTIVITIES: (1) Address reviewer comments for Los Angeles (project #3), (2) Resubmit Seattle (project #2) manuscript for review, and (3) Finalize and submit the Final Project Report.

PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez, and Ph.D. Student Kendall Wnuk.

TITLE OF THE PROJECT: Study of Tunnel-Induced Ground Settlement Using Integrated Machine Learning and Remote Sensing Techniques

SUMMARY: For urban tunnel constructions, the ground settlement should be limited within a tolerable threshold to prevent damage to aboveground structures. Analysis and prediction of tunnel-induced ground deformation are vital both in the tunnel design and construction planning stages. This project will integrate machine learning methods and remote sensing methods to study tunnel-induced ground surface settlements. The overarching goals that this project attempts to accomplish include 1) predicting tunnel-induced ground deformations using machine learning methods, 2) predicting accumulated ground deformations using time-series machine learning techniques, and 3) analyzing ground settlements using integrated Gaussian Mixture Model and interferometric synthetic aperture radar (InSAR) imageries.

PROJECT STATUS: This project has started in September 2019, has completed the first objective, and partially completed the second objective. Seven shallow-structure and deep-structure machine learning methods have been applied to the prediction of tunnel-induced ground settlement, including multiple linear regression (MLR), decision tree (DT), random forest (RF), gradient boosting (GB), support vector regression (SVR), back-propagation neural network (BPNN), and a permutation-importance-based BPNN (PI-BPNN) models. The effectiveness of these seven machine learning approaches on small datasets has been evaluated using model accuracy and stability. Six important contributing factors of the ground settlement have been identified. Autoregression integrated moving average (ARIMA) and time-series machine learning models have been used to analyze and predict accumulated tunnel-induced ground settlement.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Seven machine learning methods have been comparatively studied in the application of predicting tunnel-induced ground settlement (January 2020); (2) One completed and submitted a manuscript entitled "Effectiveness of predicting tunneling-induced ground settlements using machine learning methods with small datasets" to the Journal of Rock Mechanics and Geotechnical Engineering–Special issues of Internet of Things (IoT) and Artificial Intelligence (AI) in Geotechnical Engineering (March 2020); and (3) Accumulated ground settlement predicted by time-series machine learning methods (March 2020)

PLANNED ACTIVITIES: The research plan for this year onward will be to finish my second paper – prediction of accumulated tunneling-induced ground settlement using time-series machine learning methods. In

addition, Sentinel-1 InSAR data will be processed and integrated with machine learning models to obtain deformation to characterize tunneling-induced differential ground deformation.
PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez, and Ph.D. student Linan Liu.

TITLE OF THE PROJECT: Adaptive, Predictive 3D Geologic Modeling for Hard Rock Tunneling
SUMMARY: The expected geology along a proposed tunnel alignment is typically characterized based on an expert geologist's interpretations of some sparse initial investigations. As a predictive model of the true subsurface geology, a 3D geologic model 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 prior to installation of the final tunnel support. These new observations can be used to both validate existing geologic models and update model uncertainty to account for previously unseen structures. During excavation, this information can be used to adapt the geologic model to unfolding ground conditions, and following excavation, the calibrated geologic model can be used to inform potential expansions in the vicinity of the existing tunnel alignment. The model discrepancy is used to formulate and assess predictions of subsurface geology in the context of a 3D geologic model. Bayesian statistics provides a convenient framework for validating and updating predictions of subsurface geology considering new observations and information. The objectives of this project are: (1) To implement a data-driven 3D geologic modeling workflow that predicts geologic structures along a tunnel alignment with quantified uncertainty and (2) To utilize additional information gathered during excavation to adapt the geologic model to encountered geology in a Bayesian framework.
PROJECT STATUS: This project started in May 2017. As of January 2021, Objective (1) is 100% complete, and Objective (2) is 75% complete. The robust workflow for geologic model uncertainty assessment developed for Objective (1) has been leveraged to assess the uncertainty about fault zones intersecting the Eisenhower-Johnson Memorial Tunnels (EJMT) in Colorado, USA. A methodology using excavation progress rate and rockmass classification information has been developed to adaptively refine geologic model uncertainty using rejection sampling for approximate Bayesian computation (ABC-REJ).
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. Continued collaboration with Seequent provides support of a proprietary Beta build of Leapfrog Geo, enabling the researchers to generate uncertainty assessments of geologic models freely and rapidly.
PLANNED ACTIVITIES: Validation of geologic models from the EJMT is being carried out using the developed ABC-REJ method, with codes being prepared for open-source publication along with a peer-reviewed journal article. A second manuscript is being expanded from the conference paper published in ARMA 2020, expanding the workflow to use the point cloud-derived rockmass structures to inform 3D interpolation of numerical rockmass properties. Thesis defense and UTC-UTI report delivery are planned to be completed in August 2021.
PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez, and Ph.D. student Ashton Krajnovich.

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 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. 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. The development of a probabilistic simulation framework for tunnel infrastructure resilience has been completed. The student working on this project has completed his thesis work and graduated. Final report was completed and submitted.

MILESTONES ACCOMPLISHMENTS AND DATES: The development of the tunnel resilience simulation framework was completed. The Ph.D. student working on the project graduated with a Ph.D. dissertation submitted to Colorado School of Mines Library by November 2020. Two additional Journal papers were submitted under review. Final report based on research findings was completed and submitted.

PLANNED ACTIVITIES: The student and PIs will continue to work on journal papers under review until they are published. No other activities were planned for this project beyond final report submission.

PROJECT PERSONNEL: Dr. Shiling Pei, Dr. Marte Gutierrez, and Ph.D. Student Sandeep Khetwal.

TITLE OF THE PROJECT: Engineering Feasibility Study of the Future Extension of the Eisenhower-Johnson Memorial Tunnel

SUMMARY: This project is in collaboration and with co-funding from the Colorado Department of Transportation (CDOT). The Eisenhower–Johnson Memorial Tunnel (EJMT) is a dual-bore, four-lane vehicular tunnel located approximately 97 km west of Denver, Colorado. EJMT connects Interstate 70 on the two sides of the Continental Divide in the Rocky Mountains. The first bore, named after Dwight D. Eisenhower, the U.S. President for whom the Interstate system is also named, opened in 1973. The second eastbound bore, named after for Edwin C. Johnson, former CO Governor and U.S. Senator who lobbied for an Interstate Highway to be built across Colorado, was completed in 1979. It is the longest mountain tunnel as well as the highest point on the US Interstate Highway System. The EJMT is the main thoroughfare for vehicles travelling between Denver and the major cities in the West in Utah, Nevada and California. The EJMT carries a large volume of traffic which continues to increase every year. In 2016, the daily vehicular count ranged from about 27,000 in November to more than 42,000 in July. EJMT has always been a choke point along I70 due to limited vehicular capacity, and traffic congestion is often aggravated by issues in the tunnel such as accidents, vehicular pileups, inspection, maintenance and repair. Traffic delays occur most of the year but are particularly significant during peak travel times and seasons. The result is significant economic losses from the delay in the movement of commuters and passengers, goods and services, and in particular in the local tourism industry specially in the several world-class ski resorts west of EJMT. EJMT is now carrying more traffic than it was designed for more than 40 years ago. The main goal of the proposed research project is to conduct a comprehensive engineering feasibility study of viable alternatives to the extension/expansion of the EJMT using the most current procedures for geological investigation and characterization; tunnel analysis, design, construction and risk analysis; and advanced tunneling and transportation guidance systems. The specific objectives of the project are: 1) Develop an updated, comprehensive and accurate geological and geotechnical characterization of the region surrounding the EJMT; 2) Formulate alternatives to future extension/expansion of EJMT including enlargement of the existing twin tunnels, and new alignments of new tunnel bores, based on the improved

geological characterization, expected future traffic characteristics and volumes along the I-70, and new/future advance guidance systems (AGS); 3) Conduct engineering studies to demonstrate the viability of the different potential alternatives to the expansion of EJMT including tunnel geometry, dimensions, excavation method and support; and 4) Conduct a study of new or future tunneling technologies and advanced guidance systems that can enhance the viability of expanding the capacity of EJMT.
PROJECT STATUS: The project is delayed due disruptions from COVID-19, however, the major project tasks are now complete. The two Ph.D. students working on the project are on track to complete their dissertations and to graduate in Spring or Summer 2021.
MILESTONES ACCOMPLISHMENTS AND DATES: The following project tasks have been completed to date: 1) An updated and comprehensive and geological and geotechnical characterization of the region surrounding the EJMT; 2) Fully digital 3D model of the geology around the existing tunnel bores; and 3) Suggested tunnel bore alignments to future extension/expansion of EJMT including enlargement of the existing twin tunnels.
PLANNED ACTIVITIES: The main task for the next reporting period is to back-analyze the response of the existing tunnel bores, then the back-analyzed response will be used to test the validity of potential tunnel geometries and supports along the suggested tunnel alignments.
PROJECT PERSONNEL: Dr. Marte Gutierrez, Ph.D. students Gauen Alexander and Ashton Krajnovic.

Research at California State University Los Angeles

TITLE OF THE PROJECT: Applications of Data Science and Big Data Analytics in Underground Transportation Infrastructure
SUMMARY: This research project focuses on the applications of data science, machine learning, and big data analytics in the construction and maintenance of the underground transportation infrastructure. (1) The first objective of this project is to develop advanced data mining and novel machine learning methods for predicting or detecting ground conditions using the data collected before and during the TBM operations; (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; (3) The third objective is to design and develop predictive models and AI techniques to predict future adverse events in UTI such as structural defects and anomalies, and defect progression and consequences over time.
PROJECT STATUS: As for the first objective, we are now working on refining the predictive model to achieve even more accurate results. We used a big dataset from Seattle Northlink project and developed a new prediction technique based on advanced Deep Recurrent Neural Network (RNN). The method is very effective in predicting the composition of soil and specifications of ground. As for the second objective, we have developed a predictive model that can predict the status of TBM and its performance in real-time. We have trained and tested it on another big dataset from LA METRO. As for the third objective, we are working on algorithms to predict the future structural defects (specifically, the crack creation and progression in concrete) using deep learning. We published a journal paper in The Journal of TRB, and submitted another paper to the Journal of Computer-Aided Civil & Infrastructure Eng.
MILESTONES ACCOMPLISHMENTS AND DATES: As for objective 1, the initial activities are accomplished. We are now working on algorithm refinement. The results demonstrate that the developed models are effective and accurate in predicting the composition of soil and specifications of ground. Objective 2 has started in Fall 2018 and is still in progress. Two initial predictive models have been developed so far for predicting TBM state/performance. The results have been presented in TRB 2020 and published in a journal in 2020. Objective 3 added to the project in Summer 2020 and is still in progress.
PLANNED ACTIVITIES: (1) Developing new data-driven and AI-based algorithms for predicting/detecting structural defects and defect progression over time; (2) Developing new methods based on more complex deep learning models that can take into account more data elements to achieve higher accuracy levels; (3) Building various predictive models based on combination of supervised and unsupervised machine

learning to achieve even higher accuracy; (4) Developing, training, and applying the proposed methods on other datasets; (5) Publishing/presenting more conference/journal papers.
PROJECT PERSONNEL: Dr. Mohammad Pourhomayoun (PI), Dr. Mehran Mazari (Co-PI), Erika Estrada Medina (MS CS Student), and Kabir Nagrecha (BS CS Student).

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

SUMMARY: 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: The progress for design and analysis of the large-scale concrete 3D printer was continued despite the campus closure. A small-scale mockup was built and tested to evaluate the performance of the gantry system.
MILESTONES ACCOMPLISHMENTS AND DATES: The project report was submitted in spring 2020.
PLANNED ACTIVITIES: The large-scale gantry concrete printer is planned to be assembled and connected to a concrete pump with adjustable pressure control.
PROJECT PERSONNEL: Dr. Mehran Mazari (PI), Dr. Tonatiuh Rodriguez-Nikl (co-PI), Siavash F. Aval (Research Associate), and Sara Gerani (Graduate CE student).

TITLE OF THE PROJECT: Continuous Automatic Detection of Cracks in Tunnels Using Machine Learning and Artificial Intelligence Techniques for Safety Monitoring

SUMMARY: Structural monitoring of the inner walls of a tunnel 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: Due to the campus closure we have not been able to conduct live experiments. The algorithms and data fusion techniques have been studied via simulations in the Gazebo environment. A navigation stack of Robot Operating System (ROS) is used for autonomous navigation, a GPS plugin is used to simulate GNSS, and AMCL is used instead of SLAM in the data fusion routines. The tracker algorithm receives the localization information from the localization algorithm, which provides the location information with about 10 cm accuracy, then navigates the autonomous system to the objective point following the path created by Path Planning algorithm.
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 technique.
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: Dr. Fred Daneshgaran (PI), Dr. Marina Mondin (co-PI), Alessandro Moro. (Telecommunications), Simone Cavallera (Computer Science), and students from Politecnico Di Tornio, Turin, Italy (if allowed, to be Visiting scholars at CSLA). Note: No UTC funds were used in support of international students and researchers.

TITLE OF THE PROJECT: Resilience and Sustainability of Underground Transportation Infrastructure
SUMMARY: The goal of this study is to assess to what extent existing guidance for sustainable and resilient infrastructure design is appropriate for use with underground transportation infrastructure. Based on this assessment, recommendations 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 final report is complete for the preceding tasks. The project will continue as part of a Research Experiences for Undergraduates (REU) program in summer 2021.
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 (resubmitted in April 2021).
PLANNED ACTIVITIES: Improve details of the preliminary VAST study using a GIS approach; assess the LA Metro Resilience Framework.
PROJECT PERSONNEL: Dr. Tonatiuh Rodriguez-Nikl (PI) and Dr. Mehran Mazari (co-PI).

Research at Lehigh University

TITLE OF THE PROJECT: Fire Resistance of Tunnel Surfaces
SUMMARY: The research effort is exploring 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, and 2) Similar panels with intumescent paint, Spray-applied Fire-Resistant Material (SFRM), 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 standard experimental panel design is used (24" x 18" x 6" normal weight concrete panels with mild reinforcement) with the following fire-exposed surface configurations: bare concrete; tiled with material used in a typical U.S. tunnel (procured from a major supplier of tunnel tile); or coated with passive fire resistance, specifically SFRM and intumescent paint (procured from two different fire protection product vendors). Intumescent paint, SFRM, and tile products and their associated surface preparation products were procured between July 2020 and January 2021. The following specimens have been tested to date: 6 bare surface control specimens, 6 tiled surface specimens (including three variations in tile installation methods), and 3 SFRM coated specimens. Due to the expanding nature of intumescent paint during heat exposure additional alterations and calibrations for the testing apparatus and procedure are currently being made to test specimens with the intumescent paint.

MILESTONE ACCOMPLISHMENTS AND DATES: (1) Literature review – January 2020. (2) Identification of surface coatings for testing – January 2020. (3) Awarded supplemental funding to expand the experimental matrix via a Pennsylvania state research program (pitapa.org) – January 2020. (4) Development of test matrix – February 2020. (5) Preliminary estimates of behavior based on previous testing – March 2020. (6) Setup and instrumentation of specimen forms and reinforcement – March 2020. (7) Fabrication of panels - June 2020. (8) Completed residual strength study – September 2020 (9) Completed 1st specimen set of bare surface control specimen testing - January 2021. (10) Completed tiled specimen testing - December 2020. (11) Completed SFRM specimen testing - April 2021

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, Dr. Spencer Quiel (lead faculty), and Dr. Clay Naito.

PROJECT TITLE: Mechanical Characterizations of Joints in Segmented Tunnel Liners Due to Flexural and Thrust Jack Loading

SUMMARY: Precast segmental tunnel liners (installed via tunnel boring machines or TBMs) have become increasingly used in modern tunnel construction. The performance of the joints (both radial and longitudinal) due to in-plane and out-of-plane loading will influence the response of the liner to fire and blast loading. The Lehigh team is working with Dr. Michael Mooney and the UTC-UTI researchers at CSM in support of an FHWA-funded test program which will have the following objectives: (1) characterize the moment-rotation response and failure modes of the radial joints between segments when subjected to a combination of out-of-plane loading and restraining arching action (i.e. in-plane ring stresses); and (2) evaluate the capacity of the longitudinal joints for thrust jack loading. These tests will be conducted at Lehigh's Fritz Laboratory by the team composed of Dr. Mooney and Lehigh research engineers with assistance from Profs. Naito and Quiel as well as their graduate students.

PROJECT STATUS: The Chesapeake Bay Tunnel was identified for the research study. A site visit to the tunnel segment fabrication site, located at 1010 Bells Mill Rd, Chesapeake, VA, was conducted and segments were instrumented and cut to facilitate laboratory testing. The test specimens were shipped and have been received by Lehigh University. The test fixtures for both thrust and flexure tests have been designed. To predict the behaviors of segmental liners under compressive load with and without eccentricity, a series of nonlinear and dynamic finite element models were created and analyzed in Abaqus. Detailed test plans for the thrust tests have been developed based on an in-depth literature review. Instrumentation planning and pre-test computational predictions are in progress.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Literature review – November 2020. (2) Tunnel liner segment fabrication, cutting, coring and instrumentation at tunnel segment fabrication site, and shipping to Lehigh University – December 2020. (3) Preliminary design of test fixtures and testing protocols for the thrust jack and joint flexure tests - March 2021. (4) Nonlinear and dynamic finite element preliminary analysis in Abaqus to predict structural response when subjected to single and double point thrust loading with realistic eccentricity considered – March 2021.
PLANNED ACTIVITIES: (1) Thrust testing of tunnel liner segments in Summer 2021. (2) Flexure testing of tunnel liner segments in Fall 2021. (3) Computational modeling and design guidance in late 2021.
PROJECT PERSONNEL: Ph.D. student Ziyan Ouyang (lead student), Ph.D. student Qi Guo, Dr. Clay Naito (lead faculty), and Dr. 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 published 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 extended 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 Ph.D. 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.
MILESTONES ACCOMPLISHMENTS AND DATES: (1) Literature review – October 2019. (2) Identification of validation cases to be used for CFD model development – November 2019. (3) Validation of CFD models against 100MW fire tests performed in the Memorial Tunnel (WV, USA) for critical velocity ventilation – March 2020. (4) Development of a first draft of the revised fast-running fire assessment model based on the validated CFD solution - March 2020. (5) Development of a preliminary beta version of a Matlab-based program to implement the fast-running fire assessment framework - January 2021. (6) Draft journal paper completed on ventilation effects - March 2021.
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 Dr. Zheda Zhu (lead), Ph.D. student Qi Guo (secondary lead), Ph.D. student Aerik Carlton, Dr. Spencer Quiel (lead faculty), and Dr. Clay Naito.

1.2.2 Student Activities[i]

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

a) A total of 24 students (12 Ph.D., 8 MS, and 2 BS) were funded by UTC-UTI. Of which 12 (11 Ph.D., 1 MS, and 1 BS) are working at CSM, 9 (8 MS and 1 BS) at CSULA, and 3 (3 Ph.D. and 1 MS) at Lehigh. All graduate students actively worked on their thesis and dissertations and are progressing towards the completion of their degrees. REU (Research Experiences for Undergraduate) students assisted the graduate students in their research. Graduate and undergraduate 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.
b) At CSM, Ph.D. Sandeep Khetwal completed the development of tunnel resilience simulation program and his thesis. He successfully passed the Ph.D. in November 2020. Former Ph.D. student Ketan Arora is now a postdoc working for UTC-UTI.
c) At Lehigh, Ph.D. student Qi Guo is on track to defend her dissertation in May 2021. Ph.D. student Ouyang completed his MSc in Sept. 2020 and is scheduled to complete his degree by September 2023. Former Ph.D. student Dr. Zheda Zhu was hired in January 2020 as postdoctoral researcher to lead Task 3 and assist the faculty with documentation and reporting.
d) At Cal State LA, David Corona, an undergraduate student, presented his research as a TRB Minority Fellow at the 2021 TRB Annual Meeting.
e) UTC-UTI students co-authored papers, and/or participated and made presentations in several conferences including the *US Rock Mechanics/Geomechanics Symposium; Transportation Research Board Annual Meeting; and ITA-AITES World Tunnel Congress; Association of Environmental and Engineering Geologists 2020 Virtual Annual Conference*; and *ASME 2020 Heat Transfer Summer Conference.* These meetings were held online due to the COVID-19 pandemic.
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. The meetings were held in hybrid manner using a combination of face to face and online gatherings.
g) UTC-UTI students continued their research using data from different tunneling projects including the *Eisenhower-Johnson Memorial Tunnel*, *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 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.

1.2.3 Outreach Activities

a) The Lehigh team has engaged both the Pennsylvania Department of Transportation (PennDOT) and industry representatives at Gannett Fleming. Feedback on the research results and direction has been solicited via regular communication.
b) CSULA has been reaching out to LA Metro Rail, collected new big datasets for training modeling, and validating the developed algorithms, and discussed potential collaborations, discussed potential project detail.
c) CSULA organized a Webinar at Cal State LA, Deep Learning and Neural Networks, Part 1 – Introduction to Deep Learning
d) Collaboration between CSM Ph.D. Ashton Krajnovich and Seequent has continued to enable research and transfer the ideas of uncertainty assessment into the industry, with the partnership recently discussing expansion from the current Leapfrog Geo Beta build into the developing Seequent EVO API. This collaboration has continued to enable the research project and transfer ideas on uncertainty assessment into the industry.
e) CSM has continued to work with CDOT on the engineering feasibility study of the future extension of the Eisenhower-Johnson Memorial Tunnel.
f) 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.
g) UTC-UTI researchers continued to actively participate in several Technical Committees in AASHTO, ADSC; TRB, ASCE, ARMA and other professional organizations.
h) Dr. Clay Naito has been a member of ACI Committee 533 Precast Panels since October 2018.
i) Dr. Spencer Quiel has been a member of the PCI Blast Resistance and Structural Integrity Committee since July 2016.

1.2.4 Leveraging UTC-UTI Funds [i]

Extensive efforts have been made by UTC-UTI PIs to engage the industry, State DOTs and other partners in leveraging UTC-UTI funds to generate additional funding 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 $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.
b) A portion of academic year salary cost share for Lehigh faculty members Spencer Quiel and Clay Naito for their time devoted to the research efforts is provided. A 50% tuition discount was provided for the support of graduate students.
c) Lehigh 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 has expanded the scope of their project Task 1.
d) Lehigh University was awarded funds from FHWA to test tunnel liners from the Chesapeake Bay Tunnel. The research leg of this work is supported by the UTC while lab testing costs will be covered by the FHWA supplement.
e) In-kind donations of fire protection materials were provided by GCP Applied Technologies and International Paint for fire testing of concrete panel specimens as part of Lehigh University's research.
f) Seequent provided licenses for software in support of UTC-UTIs research on "*Adaptive, Predictive 3D Geologic Modeling for Hard Rock Tunneling*." Ph.D. student Ashton Krajnovich is working with Seequent in the computer implementation of his geologic model.

g) Maptek provided several free licenses for their PointStudio and Vulcan software to be used by UTC-UTI students for their studies and research.
h) Skanska-Traylor Bros. provided access to the *LA Regional Transit Connecto*r Project. Jay Dee Contractors provided in-kind support from their projects the *Seattle Northlink Extension Project* analysis.
i) Lane Construction Company has provided 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."
j) Tongji University in China provided valuable data on: 1) The *construction of MuZhai Ling Tunnel* in China, and 2) The operation and maintenance of a *Metro Subway Tunnel in Shanghai, China.*
k) Lehigh University is actively interacting with PennDOT and AASHTO T20 Committee on the UTC-UTI research projects.

1.2.5 Faculty and Researcher Accomplishments[i]

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 Rock Mechanics Research Award from the American Rock Mechanics Association, and the 18th Advanced Powder Technology Distinguished Paper Award from the Society of Powder Technology Japan. He served in the organizing committee of two international conferences.
b) Dr. Mohammad Pourhomayoun, CSULA, received new grants from NASA for projects focusing on various applications of AI in Urban Sustainability.
c) Dr. Mazari, CSULA, co-organized the Inaugural Virtual Panel Series on Sustainable Transportation Infrastructure hosted by the ASCE Transportation & Development Institute.
d) Dr. Rodriguez-Nikl was invited to facilitate discussions at the NSF-funded "Socio-Resilient Infrastructure Workshop."
e) UTC-UTI faculty member Dr. Clay Naito at Lehigh University had five accepted or published journal papers and contributed to one conference presentation from October 2020 through March 2021.
f) UTC-UTI faculty member Dr. Spencer Quiel at Lehigh University had six accepted or published journal papers and delivered one conference presentation from October 2020 through March 2021.

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 in: https://zenodo.org/communities/utc-uti/.

Project Reports

The following final project reports have been submitted to TRID and posted in Zenodo:

Arora, S. and Kaunda, R.B. (2018), "Linear Cutting Machine Tests on Microwave-Irradiated Granodiorite," *UTC-UTI Report 001.*

Lu, H. and Gutierrez, M. (2020), "Uncertainty Analysis in Rock Mass Classification and its Application to Reliability Evaluation in Tunnel Construction," *UTC-UTI Report 002.*

Epel, T., Mooney, M. and Gutierrez, M. (2020), "Ground-Structure Interaction of Twin Board Tunnels and Cross-Passages in Soft Ground Pressure Balance Tunneling," *UTC-UTI Report 003.*

Lu, H., Gutierrez, M. and Kim, E. (2020)," Uncertainty Analysis in Rock Mass Classification and its Application to Reliability Evaluation in Tunnel Construction," *UTC-UTI Report 004.*

Arora, K., Gutierrez, M. and Hedayat, A. (2020), "Experimental Study of the Tunnels in Squeezing Ground Conditions," *UTC-UTI Report 005.*

Khetwal, S., Pei, S. and Gutierrez, M. (2020), "Uncertainty Analysis in Rock Mass Classification and its Application to Reliability Evaluation in Tunnel Construction," *UTC-UTI Report 006.*

Rodriguez-Nikl, T. and Mazari, M. (2020), "Resilience and Sustainability of Underground Transportation Infrastructure: Climate Vulnerability and Sustainability Assessments," *UTC-UTI Report 007.*

Pourhomayoun, M. Nagrecha, K., Mazari, M. and Rodriguez-Nikl, T. (2020), "The Applications of Data Science and Big Data Analytics in Underground Transportation Infrastructure," *UTC-UTI Report 008.*

Mazari, M., Ava, S. and Rodriguez-Nikl, T. (2020), "Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Infrastructure Applications*," UTC-UTI Report 009.*

Selected Journal Publications:

Arora, K., Gutierrez, M. and Hedayat, A. (2021), "Time-dependent Behavior of the Tunnels in Squeezing Ground: An Experimental Study," Rock Mechanics and Rock Engineering, Vol. 54, pp. 1755-1777.

Arora, k., Gutierrez, M., and Hedayat, A. (2021). "New Physical Model to Study Tunnels in Squeezing Clay-Rich Rocks," Geotechnical Testing Journal, vol. 44.

Arora, K., Gutierrez, M., Hedayat, A. and Xia, C. (2020), "Tunnels in Squeezing Clay-Rich Rocks," Underground Space.

Braathen, A., Petrie, E., Nystuen, T., Sundal, A., Skurtveit E., Zuchuat, V., Gutierrez, M., Midtkandal, I. (2020), "Interaction of deformation bands and fractures during progressive strain in monocline - San Rafael Swell, Central Utah, USA," Journal of Structural Geology, Vol. 141, December 2020, 104219.

Cercone, C., Naito, C., Hendricks, R. and Sause, R. (2021), "Composite Steel Tee Concrete Deck Bridge System: Performance of Interface Shear Connection," ASCE Bridge Journal, Vol. 26, No. 3, Mar. 2021.

Doorn, N., Michelfelder, D.P., Barrella, E., Bristol, T., Dechesne, F., Fritzsche, A., Johnson, G., Poznic, M., Robison, W., Sain, B. , Stone, T., Rodriguez-Nikl, T., Umbrello, S. , Vermaas, P. E. and Wilson R.L. (2020). "Reimagining the Future of Engineering," The Routledge Handbook of the Philosophy of Engineering, D. P. Michelfelder and N. Doorn (eds.), Routledge.

Drury, M., Kordosky, A. and Quiel, S. (2020), "Structural Fire Resistance of Partially Restrained, Partially Composite Floor Beams, II: Modeling," Journal of Constructional Steel Research, Vol. 167, April 2020.

Fathi, A., Tirado, C., Rocha, S., Mazari, M. and Nazarian, S. (2021), "Assessing Depth of Influence of Intelligent Compaction Rollers by Integrating Laboratory Testing and Field Measurements," Transportation Geotechnics, Vol. 28, 100509.

Frash, L.P., Fu, P., Morris, J., Gutierrez, M., Neupane, G., Hampton, J., Welch, N.J., Carey, J.W. and Kneafsey, T. (2021), "Fracture Caging to Limit Induced Seismicity," Geophysical Research Letters, Vol. 48, no. 1, January 2021.

Gombeda, M., Naito, C. and Quiel, S. (2021), "Flexural Performance of Precast Concrete Insulated Wall Panels with Various Configurations of Ductile Shear Ties," Journal of Building Engineering, Vol. 33, January 2021.

Kolay, C., Al-Subaihawi, S., Marullo, T., Ricles, J. and Quiel S. (2020), "Multi-Hazard Real-Time Hybrid Simulation of a Tall Building with Damped Outriggers," International Journal of Lifecycle Performance Engineering (Inderscience), Vol. 4, No. 1-3.

Kordosky, A., Drury, M. and Quiel, S. (2020), "Structural Fire Resistance of Partially Restrained, Partially Composite Floor Beams, I: Experiments," Journal of Constructional Steel Research, Vol. 167, April 2020.

Krajnovic, A., Zhou, W. and Gutierrez, M. (2020), "Uncertainty Assessment for 3D Geologic Modeling of Fault Zones Based on Geologic Inputs and Prior Knowledge," Solid Earth, Solid Earth, Vol. 11, pp. 1457–1474.

Lu, M., Sua, L., Gutierrez, M., Zhang, Y., Chen, K. and Zheng, B. (2020), “Verification of Fracture Reorientation and Analysis of Influence Factors in Multiple Fracturing Treatment,” Geofluids, Article ID 2457814, 13 pp

Ma, S. and Gutierrez, M. (2020), “Determination of the Poroelasticy of Shales,” Acta Geotechnica, Vol. 16, pp. 581–594.

Ma, S. and Gutierrez, M. (2021), “Coupled Damage-Plasticity Modelling of Saturated Shale under Undrained Condition,” Journal of the Korean Society of Civil Engineers, Vol. 25, pp. 316–325.

Mazari, M., Aval, S. F., Satani, S. M., Corona, D. and Garrido, J. (2021), “Developing Guidelines for Assessing the Effectiveness of Intelligent Compaction Technology,” Mineta Transportation Institute.

Mifkovic, M., Swidinsky, A. and Mooney M.A. (2021) “Imaging ahead of a Tunnel Boring Machine with DC Resistivity: A Laboratory and Numerical Study,” Tunnels and Underground Space Technology, 2021, 108 103703.

Nagrecha, K., Fisher, L., M. Mooney, M., Alavi, E., Rodriguez-Nikl, M. Mazari , T.and M. Pourhomayoun, M. (2020), “As-Encountered Prediction of Tunnel Boring Machine Performance Parameters Using Recurrent Neural Networks,” The Journal of the Transportation Research Board, July 2020.

Naito, C. (2020), “Construction and Field Evaluation of Electrically Isolated Tendons in a Prestressed ConcretSpliced Girder Bridge,” Case Study, ASCE Bridge Journal, Vol. 25, No. 7, July 2020.

Naito, C., Hendricks, R., Sause, R. and Cercone, C. (2021), "Composite Steel Tee Concrete Deck Bridge System: Design, Fabrication, and Full-Scale Verification," ASCE Bridge Journal, Vol. 26, No.1, Jan. 2021.

Oswald, C. and Quiel, S. (2020), “Design of Load-Bearing Precast Concrete Buildings to Resist Progressive Collapse,” PCI Journal, Vol. 65, No. 5, September 2020.

Prassetyo, S.H. and Gutierrez, M. (2020), “Hydro-Mechanical Response of Excavating Tunnel in Deep Saturated Ground,” International Journal of Geo-Engineering, Vol. 11, article no. 21.

Rodriguez-Nikl, T. (2021), “Technology, Uncertainty, and the Good Life: A Stoic Perspective,” Philosophy and Engineering: Reimagining Technology and Social Progress, Z. Pirtle, D. Tomblin, and G. Madhavan (eds.), Springer.

Shirole, D., Hedayat, A., and Walton, G. (2020), “Illumination of Damage in Intact Rocks by Ultrasonic Transmission-Reflection and Digital Image Correlation,” Journal of Geophysical Research-Solid Earth, 125:7.

Wang, P.Y., Garlock, M.E.M., Zoli, T.P. and Quiel, S.E. (2021), “Low-frequency Sinusoids for Enhanced Shear Buckling Performance of Thin Plates.” Journal of Constructional Steel Research, Vol. 177, February 2021.

Wu, S., Gan, Y., Hampton, J., Gutierrez, M., Lu, M. and Huang, X. (2020), “A Time-Field Search Method for AE Source Location with a Regional Velocity Model,” Acta Geophysica, Vol. 68, pp. 1335–1344.

Xu, G. and Gutierrez, M. (2021), “Damage Evolution in Secondary Tunnel Lining Under the Combined Actions of Corrosion Degradation of Preliminary Support and Creep Deformation of Surrounding Rock,” Transportation Geotechnics, Vol. 27, March 2021.

Zhang, N., Hedayat, A., Figueroa, L., Bolaños Sosa, H.G., González Cárdenas, J.J., Salas Álvarez, G.E., Acuña Rivera, V.B. (2020), “Size Effect on the Compressive Strength of Geopolymerized Mine,” Tailings & Mine Waste 2020, November 15-18, 2020.

Zhu, M., Gutierrez, M. Zhu, H., Ju, J.W. and Sarna, S. (2021), “Performance Evaluation Indicator (PEI): A New Paradigm to Evaluate the Competence of Machine Learning Classifiers in Predicting Rockmass Conditions,” Advanced Engineering Informatics, Vol. 47, January 2021, 10123.

Zhu, Z. and Quiel, S. (2021), “Near-Field Radiant Heat Flux from Open-Air Gasoline and Diesel Pool Fires: Modified Point Source and Discretized Solid Flame Models.” Fire Technology.

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

Caspar, J., Bravo, J., Wang, S., Abdulridha, A., Neti, S., Romero, C., Naito, C., Sulieman, M., Quiel, S., Yao, Z. and Oztekin, A. (2020), "Thermal Performance of Sensible Energy Storage Module Consisting of a Cementitious Matrix- the Effect of Operating Conditions," ASME 2020 Heat Transfer Summer Conference, SHTC 2020-12361, July 12 - 16, 2020, Orlando, FL, USA.

Corona, D. J., Aval, S. F. and Mazari, M. (2021), "Invited Student Paper-Life-Cycle Assessment and Cost Analysis of Using Intelligent Compaction for Construction of Asphalt Pavement Layers," Transportation Research Board Annual Meeting, No. TRBAM-21-02893.

Gangrade, R., Trainor-Guitton, W. and Mooney, M. (2020), "An Integrated Framework to Optimize Site Investigations for Tunneling Applications," ITA-AITES World Tunnels Congress, Kuala Lumpur, Malaysia, Sept 15-21, 2020.

Grasmick, J., Maxwell, A., Mooney, M. and Gangrade R. (2020), "Probabilistic Subsurface Modeling in Tunneling Applications: Is it Useful?" ITA-AITES World Tunnels Congress, Kuala Lumpur, Malaysia, Sept 15-21, 2020.

Krajnovich, A., Alexander, G., Gutierrez, M. and Zhou, W. (2020), "Historic Analysis and Future Expansion of the Eisenhower-Johnson Memorial Tunnel – Part 1: Geologic Modeling," Association of Environmental and Engineering Geologists 2020 Virtual Annual Conference, September 16-18, 2020.

Naito, C. (2020), "Construction and Field Evaluation of Electrically Isolated Tendons in a Precast/Prestressed/Post-Tensioned Concrete Spliced Girder Bridge - Coplay Bridge (S.R. 704)," ATLSS Report No. 20-03, ATLSS Center, Lehigh University, April 2020.

Ouyang, Z., Guo, Q., Naito, C., Quiel, S., "Vulnerability of Roadway Tunnel Drop Ceilings to Fire-Induced Damage," Transportation Research Board 100th Annual Meeting, virtual event, January 28, 2021.

Rodriguez-Nikl, T. and Schlemer, L.T. (2021). "A first look at resilience in both an HSI and a PWI during the COVID-19 pandemic,"3rd Annual Conference of the Collaborative Network for Engineering and Computing Diversity (CoNECD).

Wang, S., Abdulridha, A., Quiel, S., Naito, C., Sulieman, M., Caspar, J., Bravo, J., Neti, S., Romero, C., Yao, Z. and Oztekin, A. (2020), "Mechanical Performance of Concrete Thermal Energy Storage Subject to Operating Thermal Demands," ASME 2020 Heat Transfer Summer Conference, SHTC 2020-12369, July 12 - 16, 2020, Orlando, FL, USA.

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 our Zenodo archiving and dissemination cite, UTC-UTI reports and publications have been *viewed 1197 times* and *downloaded 2731 times*.

2.3 Technologies or techniques

Several technologies and techniques are currently in development at CSM 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.

Lehigh Developed a beta version of a Matlab-based program to implement the fast-running fire assessment framework.

CSULA is deploying novel techniques in their projects including: a) Novel deep learning models was developed for predicting future structural defects in underground transportation infrastructure that can be used for predicting the future status of the infrastructure and improve the risk management and maintenance efficiency. The preliminary version of the algorithm can specifically predict crack and crack progression on concrete over time; b) Novel machine learning model was developed for predicting or detecting ground conditions and soil composition using the data collected before and during the TBM operations. An advanced Deep Recurrent Neural Network (RNN) was developed and trained as a new efficient prediction technique; c) Data-driven predictive models were designed and developed that can predict the TBM state and performance in real-time (during the boring process) as well as adverse events in UTI such as structural defects, and anomalies (e.g. hitting a solid object such as metal or rock during boring) using Deep Recurrent Neural Network (RNN) and Deep Autoencoder Networks.

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); 16) Gannett Fleming (Harrisburg, PA); and (17)GCP Applied Technologies (Cambridge, MA).
c) Representatives from the following organizations have *given presentations in the UTC-UTI co-sponsored seminar series:* Purdue University School of Engineering and Technology (West Lafayette,

IN); HNTB Corporation (Seattle, WA); University of Illinois Urbana Champaign (Urbana and Champaign, IL): Arizona State University (Tempe, AZ); Bernard Catalano (Miami, FL); and University of Vigo (Vigo, Spain);

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 24 students and four 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 and participation in conferences of UTC-UTI, its faculty, researchers and students. Nevertheless, the Center is on track with its projects, reporting and dissemination.

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