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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 15 research projects (8 at CSM, 4 at CSULA and 3 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 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.

PROJECT STATUS: (Obj. 1) Work on 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 Haotian Zheng is continuing with his research on reliability-based analysis of the cross-passage excavation and expects to finish in Fall 2021. He has one journal paper accepted and two more in progress.
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, and Ph.D. students Tamir Epel and Haotian Zheng.

PROJECT TITLE: Developing Machine Learning (ML) Techniques to Predict Tunnel Performance and Stability

SUMMARY: Uncertainties associated with tunnel geology can significantly hamper tunneling progress. Various research works have tried to reduce such uncertainties by predicting the geological condition during tunnel excavation. However, specific tunneling responses caused by adverse geology are still poorly studied. In rocks, adverse geology such as karstic caves and fault zones can cause tunnel boundary collapse, a detrimental tunneling response causing unexpected interruptions and casualties. This research aims to develop Machine Learning (ML) techniques for early prediction of collapse incidents in rocks during tunnel boring machine (TBM) operation utilizing TBM and geological survey data. It is envisioned that the project will be beneficial to the practicing tunnel engineers, operators, and experts to interpret better TBM response against collapsing ground conditions and choose appropriate measures of precautions.
PROJECT STATUS: Three Machine Learning (ML) classifiers, namely: 1) multilayer perceptron, 2) support vector machine, and 3) random forest were developed to identify and predict the potential collapse of TBM tunnels in rocks. The ML algorithms are trained and validated using data on collapse incidents in a water conveyance tunneling project. The prediction accuracy of the proposed model reached 98% for training data and 96% for validation data. Furthermore, the model can identify an "Influence Zone" for a collapse incident. A unique contribution of this research is that the "Influence Zone" enables the model to predict not only an impending tunnel collapse but also the extent of that collapsed segment ahead of the excavation. Finally, to gain better insight into the ML-based predictions, the relationships between TBM -related features and tunnel geology is carefully analyzed.
MILESTONES ACCOMPLISHMENTS AND DATES: Ph.D. student Sharmin Sarna has completed a paper that was submitted to a journal. She also made an online presentation in the Mechanistic Machine Learning and Digital Twins for Computational Science, Engineering & Technology, An IACM Conference.
PLANNED ACTIVITIES: Sharmin Sarna will defend her Ph.D. dissertation proposal in early November and will work on two more journal papers on the application of ML to tunneling.
PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Mike Mooney, postdoc Anuradha Khetwal, and Ph.D. student Sharmin Sarna.

PROJECT TITLE: Effects of Tunnel Location on Slope Stability

SUMMARY: Tunnels are essential components of surface transportation infrastructure in mountainous areas. Digging tunnel through the ground is often the only way to connect geographical locations that will ensure the shortest and safest routes. One use of tunnels is to avoid the passage of roads through landslide-prone areas. However, the reverse situation is also possible, that is, construction of a tunnel can aggravate the stability of natural slopes and trigger landslides. For example, the construction of the East

Plaza of the Eisenhower-Johnson Memorial Tunnel (EJMT) in the 1960s triggered a landslide of major proportions, which was only fully stabilized almost a decade later. Therefore, it is crucial to determine if a slope nearby a potential tunnel location is sufficiently stable or if it is necessary to select a new location for the construction of the new tunnels. This is a problem faced by CDOT in selecting locations for potential new tunnel bores that will be needed in the future to alleviate traffic congestion in the existing EJMT.
PROJECT STATUS: The current project started in June 2021 with an MS student.
MILESTONES ACCOMPLISHMENTS AND DATES: The student has completed a literature review on slope stability analyses and has gathered data.
PLANNED ACTIVITIES: The MS student working on this project will develop programs for slope stability analysis techniques using Excel and use the programs to analyze different scenarios on the influence on a new tunnel excavation on the stability of an existing slope. The results will be used in helping the selection of tunnel portals and alignments for additional tunnel bores that will be excavated to help ease traffic congestion in EJMT.
PROJECT PERSONNEL: Dr. Marte Gutierrez and MS student Simon Baeza-Faundez.

PROJECT TITLE: Study of Tunnel-Induced Ground Settlement Using Integrated Machine Learning and Remote Sensing Techniques
SUMMARY: Tunneling-induced ground deformation in urban areas should be limited within a tolerable threshold to prevent damages to aboveground structures. This project integrates machine learning (ML) and remote sensing methods to study tunnel-induced ground surface settlements. The overarching goals that this project attempts to accomplish include predicting tunnel-induced ground deformations using machine learning methods and analyzing ground settlements using time-series analysis of Interferometric Synthetic Aperture Radar (InSAR) imageries. Specifically, the objectives of this project are: (1) To assess the effectiveness of predicting tunneling-induced ground settlements using ML methods with small datasets. (2) To propose a Physics-informed ensemble machine learning framework for better predicting tunneling-induced ground settlement. (3) To analyze the accumulated tunneling-induced ground deformation using time-series InSAR analysis
PROJECT STATUS: This project has started in September 2019 and has completed the first two objectives. The third objective has been partially met. For the third objective, Sentinel-1 data covering downtown Los Angeles have been downloaded and pre-processed. Persistent Scatterers Interferometry (PSI) technique will be applied, which can be achieved by GAMMA and StaMPS software. The computer program script for time-series analysis has been written.
MILESTONES ACCOMPLISHMENTS AND DATES: (1) The first paper entitled "Effectiveness of predicting tunneling-induced ground settlements using machine learning methods with small datasets" has been accepted by the Journal of Rock Mechanics and Geotechnical Engineering (August 2021). (2) The second journal paper entitled "Physics-informed ensemble machine learning framework for better predicting tunneling-induced ground settlement" had been finished and ready to submit (September 2021). A third paper is under development.
PLANNED ACTIVITIES: The research plan for this year onward will be to process InSAR data using time-series analysis. In addition, the accumulated tunneling-induced ground surface deformation will be combined with the underground physics model to obtain the three-dimensional deformation pattern. Correspondingly, the third paper related to the time-series analysis of InSAR data is underway to be finished.
PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez, and Ph.D. Student Linan Liu.

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 has the potential to aid in improving geologic understanding

and to provide a baseline for subsequent design and analysis. The initial geologic model inherits uncertainty from input data and interpretations. As tunneling progresses in a hard rock setting, information on the encountered geologic conditions can be collected prior to installing the final tunnel support. These new observations can be used to 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 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 September 2021, Objective (1) is 100% complete, and Objective (2) is 75% complete. The robust workflow for geologic model uncertainty assessment developed for Objective (1) is 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 model validation is underway.
MILESTONES ACCOMPLISHMENTS AND DATES: Two journal article manuscripts are being prepared for publication on Objective (2) and previously published conference papers and a journal article. Collaboration with Seequent has led to developing a proprietary Beta build of Leapfrog Geo, enabling the researchers to freely and rapidly generate uncertainty assessments of geologic models. The Case study for the Eisenhower-Johnson Memorial Tunnels is completed.
PLANNED ACTIVITIES: Two manuscripts for peer-reviewed journals are being completed. The first manuscript explores Bayesian inference for model updating based on tertiary information collected during tunnel excavation. The second manuscript expands the conference paper published in ARMA 2020, focusing on deriving 3D structural geologic modeling insights from outcrop point cloud data.
PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez, and Ph.D. student Ashton Krajnovich.

PROJECT TITLE: Experimental and Analytical Modeling of Tunnels in Squeezing Ground Conditions
SUMMARY: The presence of squeezing ground conditions often poses significant challenges in predicting tunnel response over time and to the design of an adequate support system to stabilize the tunnel. Over the years, many methodologies have been proposed to predict squeezing in tunnels based on tunnel depth, in situ stress, ground mineralogy, and ground strength and deformation behavior. Most of these methodologies are problem-specific and limited in scope. The research presented in this thesis was focused on improving the understanding of tunnel squeezing via a unique physical model test that simulated tunnel boring machine (TBM). The study consisted of four parts consisting of: a) case studies of tunnels constructed in squeezing clay-rich rock to identify critical parameters contributing towards squeezing and the development of a squeezing index for predicting the squeezing potential of tunnels; b) development of a novel physical model test to simulate a true-triaxial tunnel boring machine (TBM) excavation in squeezing ground conditions with a miniature TBM that can excavate a model tunnel into rock samples; c) experimental study of the behavior of supported and unsupported tunnels under various loading conditions; and d) the formulation of analytical models for time-dependent tunnel longitudinal displacement profile (LDP) for unsupported and supported tunnels and a convergence-confinement method to predict time dependent loads of tunnel support. The results of the research can be used to improve analysis and design of tunnels in squeezing ground.
PROJECT STATUS: This project is now on its final stages with the completion and submission of journal and conference papers.

MILESTONES ACCOMPLISHMENTS AND DATES: Ketan Arora, who was responsible for this project has completed his Ph.D. degree and was hired as postdoc following the completion of his Ph.D. Five journal papers and eight conference papers were completed, submitted, and published. One more journal paper is in review. The final project report has been posted in Zenodo and submitted to different submission portals.
PLANNED ACTIVITIES: Ensure acceptance and publication of the sixth journal paper that were produced from the project.
PROJECT PERSONNEL: Dr. Marte Gutierrez, Dr. Reza Hedayat, and Ph.D. Student Ketan Arora.

PROJECT TITLE: 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

PROJECT TITLE: Simplified Calculation of Liner and Soil Deformations in Tunnels Subjected to Internal Explosions
SUMMARY: This project responds to a need for simplified tools for determining the behavior (primarily residual deformations) of tunnels subjected to internal explosions. The contribution of the soil will be included through a Winkler (distributed springs) foundation with yielding springs. An equivalent single degree of freedom (SDOF) approach will be used. Because of the use of the Winkler foundation, established SDOF approaches cannot be used directly; the equivalent mass, stiffness, and load factors need to be derived from first principles. The model will be calibrated and verified with existing data and explored parametrically.
PROJECT STATUS: The student researcher is being hired. Preliminary work was performed over the previous summer (as part of an REU program) to review the literature, conduct a proof-of-concept study (elastic foundation no liner resistance), and finalize the project scope.
MILESTONES ACCOMPLISHMENTS AND DATES: Summer 2021 – preliminary literature review, proof of concept study, finalization of project scope. Fall 2021 – hiring process underway for student research assistant.
PLANNED ACTIVITIES: (1) Development of SDOF model to incorporate soil yielding and liner resistance, (2) calibration of the model, in particular the effective depth for the soil spring, (3) parametric analysis, (4) final recommendations and report.
PROJECT PERSONNEL: Tonatiuh Rodriguez-Nikl (PI), Undergraduate or graduate student (to be named), and Leo Torres or designee (Industry collaborator).

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 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: We have completed the first objective. We are now working on refining the predictive model to achieve even more accurate results. We have developed a new prediction technique based on advanced Deep Recurrent Neural Network (RNN). The model 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 have developed algorithms that predict the future infrastructure defects including crack creation and progression in concrete. The predictive model can predict the pattern of crack progression over time using deep learning.

In addition to our previous publications, we have published a new paper on "Infrastructure Defect Monitoring and Forecasting," and presented it in IPCV'21 conference in July 2021.
MILESTONES ACCOMPLISHMENTS AND DATES: As for objective 1, the initial activities are accomplished. The results demonstrate that the developed models are effective and accurate in predicting the composition of soil and specifications of ground. As for the objective 2, 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. Although the objective 3 has added to the project recently, we have developed effective models to predict the future infrastructure defects including crack creation and progression. The results have been recently published/presented. This research 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: Mohammad Pourhomayoun (PI), Mehran Mazari (Co-PI), Erika Estrada Medina (MS CS Student), and Kabir Nagrecha (BS CS Student).

PROJECT TITLE: 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 assembly of the large-scale concrete 3D printer has been started on Cal State LA's campus. The analytical model for simulation of 3D printing process is also under development.
MILESTONES ACCOMPLISHMENTS AND DATES: The project report was submitted in spring 2020.
PLANNED ACTIVITIES: The assembly of the large-scale gantry concrete printer is planned to be completed by the end of fall semester. The preliminary results of the simulation model are also expected to be produced.
PROJECT PERSONNEL: Mehran Mazari (PI), Tonatiuh Rodriguez-Nikl (co-PI), and Sara Gerani (Graduate CE student).

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, both during construction and use, is important for safety, performance, liability, and cost. The goal of this project is to develop a fully automated system to perform continuous monitoring of tunnels during and after construction. This project addresses development of data acquisition techniques, post-processing techniques, algorithms for pattern detection and classification, and localization.
PROJECT STATUS: The focus in this period has been on sensor data fusion for indoor localization and path planning and autonomous navigation. Laboratory activities have resumed and construction is complete

on a robotic test platform specifically for sensor data fusion experiments. Sensor fusion based on nonlinear Kalman filtering is performed with information coming from different sensors: (a) wheel encoders and IMU measurements for relative odometry, (b) GNSS receiver for absolute position estimates, and (c) landmarks for absolute position and orientation information. This method has been tested in simulation only.

MILESTONES ACCOMPLISHMENTS AND DATES: Vehicle based data acquisition systems were designed, developed, implemented, and tested in 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 defects. An indoor localization technique using stereo cameras was designed, developed, implemented, and tested in 2019. Further integration of this system with Global Navigation Satellite Systems was conducted in 2020.

PLANNED ACTIVITIES: The next objective is to design, develop and implement a hierarchical path planning and tracking algorithm that can provide cm-level localization and tracking accuracy. The technique is based on vision localization in which the stereo camera detects a QR code, calculates the distance and orientation, then the algorithm navigates the autonomous system. An obstacle avoidance system will be included.

PROJECT PERSONNEL: Fred Daneshgaran (PI), 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).

Research at Lehigh University

PROJECT TITLE: Year 5 Task 1 - 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.
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); and coated with passive fire resistance, specifically SFRM and intumescent paint (procured from two different fire protection product vendors). Intumescent paint, SFRM, and tile products (including their associated surface preparation products) were procured between July 2020 and January 2021. All specimens have now been tested. This includes 6 bare surface control specimens, 6 tiled surface specimens (including three variations in tile installation methods), 3 SFRM coated specimens, and 3 intumescent paint specimens. The results have been summarized and submitted to the Transportation Research Board as a paper for consideration in the 2022 TRB Conference and Transportation Research Record.

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. (12) Completed intumescent paint testing – June 2021. (13) Submitted paper for consideration at TRB Annual Meeting – August 2021.
PLANNED ACTIVITIES: (1) Incorporate results into computational modeling efforts for heated concrete surfaces; (2) compile report for UTC archiving.
PROJECT PERSONNEL: Ph.D. student Aerik Carlton (lead student), Ph.D. student Saidong Ma, Ph.D. student Qi Guo (graduated in May 2021), Prof. Spencer Quiel (lead faculty), and Prof. Clay Naito.

PROJECT TITLE: Year 5 Task 2 - 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 Prof. 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 Prof. 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 as the prototype 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. All thrust tests have been completed, a draft report was developed and is under review. The flexure tests are pending on review by our CSM partners and external review committee from WSP Engineering Consultants.
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. (5) Experimental Testing of thrust load demands on liners – June 2021. (6) Test summary report on thrust loads submitted to WSP – July 2021. (7) Comprehensive thrust load evaluation report draft completed – September 2021.
PLANNED ACTIVITIES: (1) Complete Technical Report on Thrust Load Test – Fall 2021. (2) Submit Journal Paper on Thrust Load Design – Spring 2022. (3) Flexure testing of tunnel liner segments – Spring 2022. (4) Develop computational modeling and design guidance as a journal paper submission – Spring-Summer 2022.

PROJECT PERSONNEL: Ph.D. student Ziyan Ouyang (lead student), Ph.D. student Qi Guo (graduated May 2021), Prof. Clay Naito (lead faculty), and Prof. Spencer Quiel.

PROJECT TITLE: Year 5 Task 3 - 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 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 has been 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. The effects of fixed firefighting systems (FFS) are also being considered in an upcoming paper submission by leveraging the enhanced software capabilities.

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. (7) Sent beta version of software tool to industry partners for comment – May 2021. (8) Completed draft paper on conduit performance under fire events – June 2021. (9) Draft paper on tunnel structure resilience under fire events – September 2021.

PLANNED ACTIVITIES: (1) Solicit feedback from industrial partners for subsequent development opportunities for the results of this research. (2) Review comments from industry partners on software and enhance tool accordingly. (3) Submit three papers on ventilation, conduits, and resilience for review. (4) Finalize optimization approach for design of fire protection of tunnels. (5) Present results at the next UTC-UTI symposium and other conference venues to disseminate the newest developments of this framework.

PROJECT PERSONNEL: Postdoctoral researcher Zheda Zhu (lead), Ph.D. student Qi Guo (secondary lead, graduated in May 2021), Ph.D. student Aerik Carlton, Prof. Spencer Quiel (lead faculty), and Prof. 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 (16 Ph.D. and MS, and 8 BS) participated in UTC-UTI projects. All graduate students actively worked on their research projects, 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) In CSM, eight graduate students (five Ph.D. and three MS) worked on UTC-UTI research projects during the reporting period. Two new MS students were recruited to join UTC-UTI starting from Fall 2021. Five Ph.D. students completed their degrees during the reporting period.
c) In Lehigh, a total of four Ph.D. students participated in projects funded by UTC-UTI during the reporting period. PhD student Guo defended her dissertation in May 2021 and has taken a position at Sandia National Laboratory. PhD student Carlton is on track to defend his dissertation in May 2022 and has completed his qualifying exam and dissertation proposal. PhD student Ouyang completed his MSc in Sept. 2020, qualifying exam in August 2021, and is scheduled to complete his degree by September 2023. PhD Student Saidong Ma has joined the team in person in 2021 and will take his Qualifying Exam in January 2022. Former Lehigh Ph.D. student Guo defended her dissertation in May 2021 and has taken a position at Sandia National Laboratory.
d) In Cal State LA, four MS students and five REU (Research Experience for Undergraduates) students were part of UTC-UTI projects.
e) Former CSM Ph.D. students Ketan Arora, Hui Lu, Tamir Epel, Sandeep Khetwal, and Rajat Gangrade are now working on transportation tunnels in construction companies.
f) CSM Ph.D. students Ashton Krajnovic and Gauen Alexander gave presentations to MapTek during their Lunch & Learn seminar.
g) Ph.D. students Carlton and Ouyang served as graduate student mentors to two undergraduate student researchers for 10 weeks during Summer 2021.
h) One Cal State LA undergraduate student was selected for 2022 TRB Minority Fellowship
i) CSULA students published Invited Student Paper on Life-Cycle Assessment and Cost Analysis of Using Intelligent Compaction for Construction of Asphalt Pavement Layers (No. TRBAM-21-02893).
j) UTC-UTI students published papers with their faculty advisers in leading journals, co-authored papers, and/or participated and made presentations in several conferences including the *US Rock Mechanics/Geomechanics Symposium; the 2021 Transportation Research Board Annual Meeting; Mechanistic Machine Learning and Digital Twins for Computational Science, Engineering & Technology, An IACM Conference; and the 25th International Conference on Image Processing, Computer Vision, & Pattern Recognition* (*IPCV'21*).
k) 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.
l) 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.
m) Two CSM graduate students continued with their engineering feasibility study of the future extension of the *Eisenhower-Johnson Memorial Tunnel* (EJMT).

n) 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) Dr. Mike Mooney, UTC-UTI Deputy Director, has created a new on-line Graduate Certificate Program on Underground Construction and Tunneling. To date, 59 industry professionals working in the construction industry have participated in the Graduate Certificate Program.
b) The Lehigh team has engaged both the Pennsylvania Department of Transportation (PennDOT) and industry representatives at Gannett Fleming and Thornton Tomasetti. Feedback on the research results and direction has been solicited via regular communication.
c) 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.
d) Collaboration between CSM Ph.D. student 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) CSULA students were involved in international collaborative opportunities for Cal State LA and Politecnico di Torino robotic groups.
g) 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.
h) UTC-UTI researchers continued to actively participate in several Technical Committees in AASHTO, ADSC, TRB, ASCE, ARMA, and other professional organizations.
i) Dr. Clay Naito has been a member of ACI Committee 533 Precast Panels since October 2018.
j) Dr. Spencer Quiel has been a member of the PCI Blast Resistance and Structural Integrity Committee since July 2016.
k) In May 2021, Prof. Quiel of Lehigh University presented at the 2021 ACEC/PA Spring Conference, session "Get to Know the PA UTCs" to raise industry awareness about the UTC-UTI site at Lehigh. He also coordinated a structural engineering demonstration and interactive activity for Lehigh University's PreLUsion Program for incoming freshman women engineering students.

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) The U.S. Defense Advanced Research Projects Agency (DARPA) has provided funds to Dr. Mike Mooney of CSM for a project to design and demonstrate rapid tunneling technology.

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-UTI while lab testing costs will be covered by the FHWA supplement. The experimental phase of the project was reviewed by WSP Engineering Consultants.
e) CSM, CSULA and Lehigh continued to work on an NSF REU (Research Experience for Undergraduates) project focused on underground construction and tunneling.
f) 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.
g) 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.
h) Maptek provided several free licenses for their PointStudio and Vulcan software to be used by UTC-UTI students for their studies and research.
i) 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.
j) 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."
k) 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.*
l) Lehigh University is actively interacting with PennDOT and AASHTO T20 Committee on the UTC-UTI research projects.
m) Karagozian & Case, Glendale, California and Sydney, Australia is collaborating with Cal State LA researchers in the development of design-friendly analytical tools to model liner and soil deformations in tunnels subjected to internal explosions. K&C's is offering cost share support in the form of senior engineer time.
n) InnoTech Systems, LLC, La Crescenta, CA. InnoTech is collaborating with Cal State LA researchers in the development of robotic technologies for condition monitoring of tunnels. Innotech is offering cost
o) In-kind donations of fire protection materials were provided by GCP Applied Technologies and International Paint to Lehigh University for fire testing of concrete panel specimens.

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, joined the editorial board of two new international journals and continued to serve as editorial board member of four other journals. He also served in the organizing committees of two international conferences. He made presentations at the 2021 Colorado School of Mines CCUS (Carbon Capture, Utilization and Storage) Expo, the InterPore 2021 Online Conference, and the 2021 ASCE Engineering Mechanics Institute Conference.
b) Dr. Mike Mooney, UTC-UTI Deputy Director, continued to work on a major project from the U.S. Defense Advanced Research Projects Agency (DARPA) to design and demonstrate rapid tunneling technology.
c) CSM faculty Wendy Zhou and Dr. Tonatiuh Rodriguez-Nikl, CSULA Director, were promoted to Full Professor.

d) CSULA researcher Dr. Mohammad Pourhomayoun received new grants from City of LA for projects focusing on various applications of AI in Urban Sustainability. He was one of the organizers for the city of Los Angeles Community Workshop on Urban Air Pollution and the Los Angeles Hackathon on Urban Air Pollution. Dr. Pourhomayoun also received new grants from NASA for projects focusing on various applications of AI in Urban Sustainability.
e) CSULA researchers Drs. Mehran Mazari and Mohammad Pourhomayoun were granted tenure and promoted to Associate Professor.
f) CSULA researcher Dr. Mehran Mazari was appointed to the Editorial Board for the California State University Journal of Sustainability.
g) CSULA researchers Dr. Mehran Mazari was invited to speak at the 2021 International Workshop on Intelligent Compaction hosted by SPARC Hub at Monash University.
h) Lehigh University faculty member Professor Clay Naito University accepted or published two journal papers and one report from April 2021 through September 2021.
i) Lehigh University faculty member Associate Professor Spencer Quiel at Lehigh University published or has been accepted four journal papers and delivered one seminar presentation from April 2021 through September 2021.
j) Prof. Quiel officially became a member of the PCI Fire Committee and is currently contributing to a white paper on performance-based design for precast concrete structures. He is also a co-author of a chapter in the recently published SFPE International Handbook for Structural-Fire Engineering.

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 posted in Zenodo, reported as complete in RIP, and submitted to DOT (research.hub@dot.gov and NTLDigitalSubmissions@dot.gov), NAS (TRIS-TRB@nas.edu), Transportation Library (r-sarmiento@northwestern.edu), Volpe National Transportation Systems Center (Susan.Dresley@dot.gov), Federal Highway Administration Research Library (FHWAlibrary@dot.gov) and National Technical Information Service (input@ntis.gov):

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. (2021), "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. (2021), "Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Infrastructure Applications*," UTC-UTI Report 009.*

Gangrade, R., Mooney, M. and Trainor-Guitton, W. (2021), "Quantifying Spatial Geotechnical Uncertainty to Advance the Practice of Risk Assessment and Decision-Making in Tunnel Projects," *UTC-UTI Report 010.*

Selected Journal Publications:

Arora, k., Gutierrez, M., and Hedayat, A. (2021). "New Physical Model to Study Tunnels in Squeezing Clay-Rich Rocks," Geotechnical Testing Journal, Vol. 44, Issue 4, July 2021.

Drury, M.M., Kordosky, A.K. and Quiel, S.E. (2021), "Robustness of a partially restrained, partially composite steel floor beam to natural fire exposure: Novel validation and parametric analysis," Journal of Building Engineering, Elsevier, submitted November 2020, published April 2021,

Epel, T., Mooney, M. and Gutierrez, M. (2021), "The Influence of Face and Shield Annulus Pressure on Tunnel Liner Load Development," Tunnelling and Underground Space Technology, Vol. 117, November 2021, 104096

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, 28, 100509.

Gheibi, A., Li, H., Hedayat, A. (2021). Detection of Seismic Precursors in Converted Ultrasonic Waves to Shear Failure of Natural Sandstone Rock Joints. Rock Mechanics and Rock Engineering 54, 3611–3627.

Guo, Q., Quiel, S. and Naito, C. (2021), "Traffic-Based Quantitative Risk Assessment of Structural Fire Damage to Roadway Tunnel Linings," Structure and Infrastructure Engineering, Taylor & Francis, Manuscript NSIE-2021-0109 submitted February 2021, accepted August 2021.

Khetwal, S., Pei, S. and Gutierrez, M. (2021), "Stochastic Event Simulation Model for Quantitative Prediction of Road Tunnel Downtime," Tunnelling and Underground Space Technology, Vol. 116, October 2021, 104092.

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

Lu, M., Wang, Z., Gutierrez, M. Chen, K., Zheng, B., Sheng, G. and Su, Y. (2021), "Apparent Porosity and Permeability Model of Inorganic Matter with Water Film in Shale Gas Reservoirs, Journal of Porous Media, Vol. 24, pp. 1-14.

Nam, S., Gutierrez, M., Diplas, P. and Petrie, J. (2021), "Laboratory and In-situ Determination of Hydraulic Conductivity and Their Validity in Transient Seepage Analysis," Water, Vol. 13, 1331.

Ouyang, Z., Guo, Q., Quiel, S. and Naito, C. (2021), "Vulnerability of Drop Ceilings in Roadway Tunnels to Fire-Induced Damage," TRR Journal of the Transportation Research Board, Sage, submitted August 2020, published July 2021.

Rodriguez-Nikl T. (2021) "Technology, Uncertainty, and the Good Life: A Stoic Perspective." In: Pirtle Z., Tomblin D., Madhavan G. (eds) Engineering and Philosophy. Philosophy of Engineering and Technology, vol 37.

Rodriguez-Nikl, T. and Rodriguez, M. (2021). "Effect of Displacement and Hysteretic Energy on Earthquake Damage in Reinforced Concrete Structures", Journal of Structural Engineering, Vol. 147 Issue 7.

Shirole, D., Hedayat, A., Walton, G. (2021). "Damage monitoring in Rock Specimens with Pre-Existing Flaws by Non-Linear Ultrasonic Waves and Digital Image Correlation." International Journal of Rock Mechanics and Mining Sciences, 142.

Wang, P.Y., Masungi, P.M., Garlock, M.E.M. and Quiel, S.E. (2021), "Postbuckling Mechanics in Slender Steel Plates Under Pure Shear: A Focus on Boundary Conditions and Load Path," Thin-Walled Structures, Elsevier, submitted February 2021, accepted September 2021.

Xu, G., Gutierrez, M., He, C. and Wang, S. (2021), "Modeling of the Effects of Weakness Planes in Rock Masses on the Stability of Tunnels Using an Equivalent Continuum and Damage Model," Acta Geotechnica, Vol. 16(7), pp. 2143-2164.

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

Arora, K. and Gutierrez, M. (2021), "Visco-Elastic-Plastic Solution for Deep Circular Tunnels in Squeezing Ground," Proc. 55th U.S. Rock Mechanics/Geomechanics Symposium, Virtual, June 2021, paper no. ARMA-2021-2156.

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

Gutierrez, M. and Prassetyo, S.H. (2021), "Coupled Hydro-Mechanical Modeling of Two-Phase Immiscible Supercritical CO_2 Flow and Transport in Saline Aquifers as Sequestration Reservoir," Proc. 2021 ASCE Engineering Mechanics Institute Conference at Columbia University in Manhattan, NY May 202.

Estrada-Medina, E. Mazari, M. and Pourhomayoun, M. (2021), "Deep Learning for Infrastructure Defect Monitoring and Forecasting," Proc. 25th International Conference on Image Processing, Computer Vision and Pattern Recognition IPCV'21, July 26-29, 2021.

Gao K., Naito C., Sulieman M., Weisman R. and Crociata, N. (2021) "Bridge Resilience in Rain Events Task 1.1 Evaluation of Backfill Properties," ATLSS Report No.21-01, ATLSS Engineering Research Center, Bethlehem, PA: Lehigh University; September 2021.

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, San Jose State University.

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 our Zenodo archiving and dissemination site, UTC-UTI reports, and publications have been *viewed 1498 times* and *downloaded 4428 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) Colorado Department of Transportation (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); (17) GCP Applied Technologies (Cambridge, MA); (18) Karagozian & Case (Glendale, California and Sydney, Australia); (19) InnoTech Systems, LLC (La Crescenta, CA); and (20) U.S. Defense Advanced Research Projects Agency (DARPA).

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 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 continued to impact many of the activities and outcomes of UTC-UTI resulting in reduced outreach activities and participation in conferences by 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.