UNIVERSITY TRANSPORTATION CENTER
FOR UNDERGROUND TRANSPORTATION INFRASTRUCTURE

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COLORADO SCHOOL OF MINES
EARTH ENERGY ENVIRONMENT

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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 proposed 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

Research at Colorado School of Mines

a) Hydro-mechanical analysis of tunneling in saturated ground using an efficient sequential coupling technique

SUMMARY: An advancing tunnel in deep saturated ground induces transient coupled interactions between fluid flow and deformation, which in turn affect the short- and long-term hydro-mechanical (H-M) response of the ground surrounding the excavation. Acknowledging this H-M interaction is thus essential for the safe design of underground excavation in saturated ground. Explicit coupling techniques have been the most attractive approach to use for simulating the H-M interaction. Yet, the techniques are conditionally stable, require small time steps, and limited to uniform grids, affecting their efficiency for long-term simulations tunnel excavation in low permeability ground. The objectives of this project are: (1) To develop a novel high-order finite difference scheme capable of solving flow problems in non-uniform grids. The pore pressure solutions from the new scheme are then sequentially coupled with an existing geomechanical simulator, resulting in an efficient sequential coupling technique. (2) To use the

new coupling technique to study the effect of the transient H-M interaction on the convergence-confinement and longitudinal displacement profile of an advancing tunnel in deep saturated ground.

PROJECT STATUS: This project has started in January 2017 and has partially completed the two objectives. The new efficient coupling technique has been developed for simulating H-M response of tunneling under plane strain conditions. The effect of transient coupling on the stress and displacement behaviors of the ground surrounding the excavation has been studied.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) The new coupling technique resulted in satisfactory H-M response of consolidation and tunneling with reduction of the computer runtime by up to 40% (May 2017). (2) New empirical relationships between the face extrusion and its convergence for tunneling in deep saturated ground will be developed (June to August 2017).

PLANNED ACTIVITIES: Research plan for this year onward will be to improve the newly-developed coupling technique for tunneling in axisymmetric conditions. In addition, new formulations for convergence-confinement and longitudinal displacement profile for tunneling in deep saturated ground will be developed.

PROJECT PERSONNEL: Dr. Marte Gutierrez and Post-doctoral Research Associate Dr. Simon Prassetyo.

b) Understanding cross passage ground-structure interaction using data from the Seattle Northgate Link transit extension project

SUMMARY: The construction of cross passages between twin bored tunnels is performed in almost all tunneling projects to satisfy emergency egress requirements. The design and construction of these cross passages is extremely challenging and, therefore, carried out conservatively throughout the underground construction and tunneling industry due to the scarcity of knowledge concerning this topic. To this end, this project aims to examine the validation of numerical modeling and analytical solutions, as compared to collected monitoring data at cross passage junctions during construction in soft soil. A rich amount of monitoring data was collected during the construction of the Northgate link extension project in Seattle, Washington. This data collection was not funded by the USDOT grant; however, we have been granted access to use the data. The information available consists of strain data from gauges installed inside the segmental liner at 17 cross passage breakouts. Additionally, convergence monitoring at the main tunnels and inside the cross passages, surface settlements monitoring, ground freezing reports, geotechnical base line report, and excavation reports are available. All of these data will be examined.

PROJECT STATUS: This project began in January 2017 and remains active. Progress to date includes two site visits to the Northlink project to learn about the project, collect the available data and study all relevant project details. The strain gauge data collected has been analyzed and translated into thrust forces and moments in the segments. These forces have been plotted throughout the construction timeline of the main tunnels and cross passages. Soil properties for each cross passage were explored using the geotechnical data reports.

MILESTONES ACCOMPLISHMENTS AND DATES: (1) Completed site visits to learn about the project and acquire all data (March 20, 2017). (2) Preliminary assessment of strain gage data including plotting with time throughout installation and construction (April 30, 2017)

PLANNED ACTIVITIES: Activities for this next reporting period will include: (1) Completing the investigative analysis of all monitoring and geotechnical data. (2) Computational modeling of the soil-structure interaction throughout staged cross-passage construction. (3) Comparison of numerical and experimental data to better understand behavior. (4) Use results to validate current design and construction practice.

PROJECT PERSONNEL: Dr. Mike Mooney, Dr. Marte Gutierrez and MS student Tamir Epel.

c) Uncertainly modeling and risk assessment in tunneling

SUMMARY: The objective of this project is to systematically assess uncertainties and risks in underground construction of a subway tunnel. Based on the available field data, risks during the life cycle of tunneling will be systematically evaluated, including: (1) before construction: geological condition; (2) during construction: construction strategy: excavation and support methods, and construction performance, e.g. advance rate, construction time and cost; (3) post-construction: operation and maintenance process, e.g. rehabilitation of tunnels. For each stage, a reasonable statistical model is to be established. Finally, a comprehensive model will be developed combining the developed models at each stage to provide support for systematic risk assessment and decision-making.

PROJECT STATUS: (1) Literature review phase (2/2017-7/2017): Review the risk management methods and tools for uncertainty modeling and risk assessment in tunneling, including Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Probabilistic Risk Analysis (PRA), Decision Tree Analysis, Bayesian Network (BN), Fuzzy Set Theory, Rock Engineering System (RES), Decision Aids for Tunneling (DAT) tool and hybrid approach combining methods mentioned above. (2) Data collection phase (3/2017-7/2017): Collect intensive tunneling data, including geology and construction information, from several metro subway line constructions in Seoul, South Korea, that are very close to each other. The effect of individual parameters on the construction performance can be investigated. Since the adjacent subway lines are constructed by different contractors in similar ground condition, the influence of different construction processes can be compared.

MILESTONE ACCOMPLISHMENTS AND DATES: (1) Preliminary literature review is complete. (2) Subway tunneling data obtained from South Korea courtesy of Ajou University.

PLANNED ACTIVITIES: (1) Model development phase (06/2017–02/2019). (2) Geologic prediction model (06/2017–11/2017). (3) Construction strategy model (11/2017–04/2018). (4) Durability model (04/2018–09/2018). (5) Combination of developed models (09/2018–02/2019). (6) Summary phase (02/2019–05/2019)

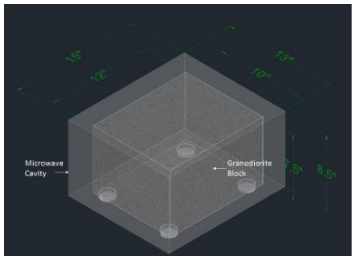
PROJECT PERSONNEL: Dr. Eunhye Kim, Dr. Priscilla Nelson, Dr. Marte Gutierrez and Ph.D. student Hui Lu.

d) New excavation technologies for underground construction

SUMMARY**:** The objective of this project is to measure energy requirements to reduce the strength of hard rock by microwave irradiation by conducting laboratory large-scale linear test experiments. Microwave irradiation is proposed as technique to aid tunneling in rocks by weakening the rock before tunneling excavation is carried out.

PROJECT STATUS: A suitable site with the suitable rock type (Boulder granodiorite) was selected, samples were collected, and currently rock cubes of a dimension 1 x 1 x 1 ft^3 are being prepared for testing (Figs. 1 – 3).

Fig. 1: Granodiorite samples collected.



2: Planned microwave treatment of rock blocks.

Fig. 3: Large-scale linear cutting test setup.

MILESTONE ACCOMPLISHMENTS AND DATES: The target is it to complete block preparation by June 30th, microwave treatment and concrete casting of blocks by July 30th, and large-scale linear cutting experiments and data analysis by August 30th.

PLANNED ACTIVITIES: Large-scale linear cutting tests will be conducted on rock samples which have been treated with microwaves. Specific energy requirements will be calculated from the test results. Specific energy values will be compared with those obtained from untreated rock samples. Benchmark physical rock properties will then be obtained using UCT (unconfined compression test), punch penetration and Cerchar Abrasivity tests on small scale rock samples.

PROJECT PERSONNEL: Dr. Rennie Kaunda and Ph.D. student Shrey Aurora.

e) Characterization of delamination processes with respect to waterjet shotcrete removal during tunnel liner repair and maintenance

SUMMARY: To circumvent the technical and operating challenges associated with conventional shotcrete removal and repair, this research seeks to develop a unique system that utilizes waterjet technology as the primary excavation tool. Building upon the success of previous CSM research activities in underground rock scaling and scarification, empiric evidence indicates that waterjets are capable of selectively removing damaged areas of support liners without structurally compromising or damaging intact material around the area being repaired. The primary research objective is to compare and contrast the unintended damage caused to the surrounding structural liner and rock substrate by both mechanical impact hammers and waterjet excavation methods during empiric testing. This analysis will involve physical testing on instrumented shotcrete panels designed to quantify fracture propagation, substrate delamination, and stress distribution. The intent of this research is to facilitate a better understanding of the dynamic excavation processes associated with liner repair in hopes of developing a future prototype system applicable for field testing.

PROJECT STATUS: Since the initiation of the research project on May 15, the project team has begun to perform detailed design and planning of the jet traverse, instrumentation of the shotcrete panels, and the testing apparatus (pump and fluid handling accessories). This work is scheduled to continue through July 21, at which time the traverse and motion system and the testing panels will be constructed. In addition, the laboratory testing methodology is also being refined and should be finalized in the next 4 weeks (scheduled for July 14). Assembly of the high-pressure pump and fluid controls will then follow and is scheduled for completion August 18. Testing at CSM's Earth Mechanics Institute is tentatively scheduled for late September, where testing at RAMAX's research lab in Southern California will be performed over Winter break in mid-December and early January.

MILESTONE ACCOMPLISHMENTS AND DATES: (1) Project Initiation: May 15, 2017. (2) Finalization of Testing Methodology: July 14, 2017. (3) Completion of Design Phase: July 21, 2017. (4) Laboratory Set-up & Testing Panels: August 11, 2017. (5) Assembly of Pump and Fluid Handling System: August 18, 2017. (6) Pre-test Analysis & Lab Testing of the Panels: Sept. 22, 2017. (7) EMI Laboratory Testing: Sept. 27-Oct. 18, 2017. (8) RAMAX Laboratory Testing: Jan. 8-12, 2018. (9) Completion of Data Analysis: April 13, 2018. (9) Project Completion and Final Report: May 14, 2018.

PLANNED ACTIVITIES: As outlined in the Project Status section, the focus of the next three months is to prepare the laboratories and research equipment for empirical testing.

PROJECT PERSONNEL: Dr. Hugh Miller, John Steele, Brian Asbury, and Ph.D. students Erik Charrier and Josef Bourgeois.

f) DC Resistivity for model Tunnel Boring Machines (TBM) in laboratory environment

SUMMARY: The project objective is to perform electrical resistivity measurements (a standard geophysical method) with a model tunnel boring machine (TBM) in artificial geologic environments. The data will then be processed and analyzed to determine the effectiveness of look-ahead resistivity techniques in various tunneling scenarios.

PROJECT STATUS: This Summer REU project started May 15, 2017. Max Mifkovic (BS completed in May 2017, MS to start in August 2017) is supported by the project.

MILESTONE ACCOMPLISHMENTS AND DATES: Modelling tank (constructed previously) is currently being modified for repeatability studies and water-based measurements using a model TBM.

PLANNED ACTIVITIES: This work will form the basis of the student's MS thesis beginning in Fall 2017. The primary goals of the summer REU research include: redesigning the model TBM, making measurements in artificial soil and water environments, and establishing the repeatability of laboratory measurements.

PROJECT PERSONNEL: Dr. Andrei Swidinsky, Dr. Mike Mooney and undergraduate student Max Mifkovic.

g) Framework for dynamic risk assessment in subsurface excavation projects

SUMMARY: Unexpected ground conditions force the designers of underground construction projects to take on unnecessary levels of risk and expense when excavating. Rigid contractual agreements exacerbate this issue by impeding the sensible modification of design plans in response to newly collected geotechnical data. Together, inflexible contractual obligations and the lack of real-time risk assessment in excavation projects result in an inability to effectively adapt design plans to unexpected ground conditions. We propose a framework for dynamic risk assessment in excavation projects, utilizing dynamic geological modeling techniques to automatically update subsurface models following the collection of new data. Lithographic modeling techniques provide a straightforward method to extrapolate information from preliminary borehole measurements to construct an initial 3-D geological model, while geostatistical modeling techniques allow for relatively easy updating of the predicted models following the addition of a wide variety of newly collected data (e.g. geophysical, remote sensing, in-situ observations). An additional benefit of using geostatistical techniques is the ability to quantify uncertainty in our model; subsurface model uncertainty plays a large role in quantifying risk, just as potentially adverse ground conditions do. Combining these two modeling techniques, a dynamic geological model is obtained which complies with initial lithographic interpretations while accounting for changes in ground conditions illuminated by newly collected data. This model also highlights where, according to collected data, we are uncertain about predicted ground conditions, allowing for a more realistic risk assessment. Additional features of the dynamic risk assessment framework will include a GIS-based data aggregation system to incorporate data into the geological model in real-time, as well as modifications to the contractual system to allow for adaptation of initial design plans to dynamically unfolding ground conditions.

PROJECT STATUS: Project started in May 2017 and a PhD student Ashton Krajnovich has joined the project.

MILESTONE ACCOMPLISHMENTS AND DATES: Submitted an abstract to the Association of Environmental and Engineering Geologists (AEG) Annual Meeting to be held in Colorado Springs, Colorado during September 12-16, 2017. Date of submission: June 1, 2017

PLANNED ACTIVITIES: (1) Literature review. (2) 3D geological modeling software comparison. (3) Prepare presentation for the AEG Annual meeting.

PROJECT PERSONNEL: Dr. Wendy Zhou, Dr. Marte Gutierrez and Ph.D. student Ashton Krajnovich.

h) Using InSAR time series analysis to characterize tunnel-induced ground surface deformation

SUMMARY: As transportation corridors reach capacity, tunneling has become an increasingly necessary means of providing infrastructure to densely populated urban areas. Tunnels are often constructed close to the surface, increasing the likelihood of excavation induced ground subsidence and the potential impact on overlying established core infrastructure such as buildings, bridges, and utility lines. It is therefore necessary to quantify surface deformation induced by tunneling processes in order to better understand the factors that contribute to surface subsidence. Interferometric Synthetic Aperture Radar (InSAR) is an ideal tool for measuring surface deformation related to tunnel construction because of its ability to make measurements with sub-centimeter accuracy over large areas, as well as the availability of historical data needed to identify any pre-construction deformation. Theoretical analysis of tunneling in homogeneous media indicates that surface settlement profiles are transversely Gaussian in shape, with maximum displacement observed directly above the center of an individual tunnel. However, surface settlement geometry is dependent upon a variety of factors including geology, water table depth, and excavation method. Here we apply Persistent Scatterer (PS) and Small Baselines Subset (SBAS) InSAR time-series techniques incorporating ascending and descending Sentinel-1 data acquired during recently completed and ongoing tunneling projects in the United States. Surface deformation measured before, during, and after tunnel excavation allows us to make inferences about subsurface conditions and better characterize the impact of tunnel excavation on overlying ground and structural deformation.

PROJECT STATUS: Project started in May 2017 and PhD student Kendall Wnuk has joined the project.

MILESTONE ACCOMPLISHMENTS AND DATES: Submitted an abstract to the Association of Environmental and Engineering Geologists (AEG) Annual Meeting to be held in Colorado Springs, Colorado during September 12-16, 2017. June 1, 2017.

PLANNED ACTIVITIES: (1) Literature review. (2) Synthetic Aperture Radar (SAR) data exploration, including data from the recent-launched Sentinel-1 satellite. (3) Preliminary data processing. (4) Prepare presentation for the AEG Annual meeting.

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

Research at California State University Los Angeles

a) Applications of data science and big data analytics in underground transportation infrastructure

SUMMARY: The research project will focus on the applications of Data Science, Predictive Analytics, Big Data Analytics, and Data Visualization in the construction, maintenance and performance of the UTIs. Data Science and Big Data Analytics are increasingly significant in the management and use of transportation systems. It is important to identify the needs for data and its capabilities and constraints. This will help us determine the impact of data science on transportation infrastructure and the innovations. Data also enables operators to manage demand conflicts, customer service, environmental impacts and innovation. The following are the objectives related to underground transportation infrastructure (UTI): (1) Data-Driven Prediction and Automated Decision Making based on the collected big data with the main goal of improving the durability and extending the life of transportation infrastructure. (2) Using Data Mining and Machine Learning Methods for Predicting or Detecting the Specifications of Ground and Geological Conditions based on the data collected before or during the TBM operations. (3) Predicting Adverse Events, and consequently, Risk/Disaster Prevention and management, and Hazard Mitigation. (4) Predicting and Detecting Structural Defects (e.g., cracks). (5) Visualization of UTI data in the most effective/optimal way. (6) Proactive Underground Transportation Infrastructure Monitoring. This is an interdisciplinary research project, which will integrate the concepts of data analytics and big data with the

engineering aspects of UTIs. The objectives of this project including developing data-driven techniques for recognizing the specifications of ground, predicting adverse events, predicting and detecting structural defects at early stage, visualization of UTI data, and UTI data analysis and monitoring for infrastructure maintenance are in line with the broader goal of "Improving the durability and extending the life of transportation infrastructure".

PROJECT STATUS: The research project includes three main phases: (1) Phase I: Large-Scale UTI Data Collection, Exploration, and Preprocessing (Task I: Research, Information and Literature Search. Task II: Data Collecting and Exploring. Task III: Data Preprocessing). (2) Phase II: Knowledge Extraction, Data Analytics, Predictive Analytics (Task I: Feature/Knowledge Extraction. Task II: Feature Selection & Data Dimensionality Reduction. Task III: Data Analytics/Predictive Analytics). (3) Phase III: Data Visualizations and Storage (Task I: Data Visualization. Task II: Data Storage, Archiving, and Accessibility).

MILESTONE ACCOMPLISHMENTS AND DATES: The project is now in Phase I, and work on Tasks I and II is on progress.

PLANNED ACTIVITIES: The following are the main planned activities regarding the Phase I of the project: Task I: Research, Information, and Literature Search (Literature Search for existing methods and resources, Research on the UTI Data, Research on Data Analytics potential applications). Task II: Collecting and Exploring Large-Scale UTI Data (Potential Sources of Data to explore: Tunnel Boring Machine (TBM) data, Vibration, Geoelectrical Signals, Pressure, Acoustic, Imaging, Geophysical Data and Specification of ground, Remote Sensing Data: Structural, Emission). Task III: Data Preprocessing (Raw Data Cleaning and Scraping, De-Noising, Removing Outliers and Bad Data, Missing Data Imputation).

PROJECT PERSONNEL: Dr. Mohammad Pourhomanyoun.

b) 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 while in use is of paramount importance for multitude of reasons including: (1) Determination of structural integrity and ultimately control of costs during the construction phase of the tunnel. (2) Continuous monitoring of the inner walls of the tunnel during operation to ensure integrity and safety of operation which again ultimately leads to control of costs via incremental repairs and timely interventions. (3) Determination of level of safety of operation of tunnels with focus on human safety and other operational and system level risk assessment, performance analysis and liability issues. The goal of this project is to develop a fully automated system to perform continuous monitoring of tunnels during and after construction. There are several key intertwined aspects to this problem that from a scientific point of view need to be deeply studied. These include but are not limited to: (1) Investigation and development of a suitable technique for relevant data acquisition. This usually involves imaging the interior walls of the tunnel, but the exact method for doing this that is a) reliable, b) cost efficient, and c) lends itself to automated detection, is an open problem. (2) Investigation and development of actual tools and techniques to acquire the data in an efficient and automated manner and communicate the information to proper processing center. (3) Investigation and development of suitable set of techniques for possible post processing of acquired data to generate an intermediate observation space on which detection algorithms may be applied. (4) Investigation and development of suitable set of algorithms and/or techniques for pattern detection and classification. (5) Investigation and development of the software suite needed for data processing from post processed data to implement selected pattern detection and classification algorithms/techniques, assess their performance and develop recommendations.

PROJECT STATUS: This project is being started where the focus is currently on exhaustive literature survey of all the techniques proposed in open literature focused on the crack detection problem, but more specifically on the crack detection as it applies to tunnels. We are also investigating machine learning and Artificial Intelligence (AI) techniques that may be applicable to this problem. Our ultimate goal is to develop an end-to-end system including the data acquisition hardware with specification of the exact method of data acquisition and the machine learning and AI software that can be used for automated crack detection. The ultimate goal is to provide a turn-key solution to this important problem.

MILESTONE ACCOMPLISHMENTS AND DATES: Our literature survey shall be completed by July 30, 2017. The deliverable shall be a report summarizing our findings and PPT presentations of some of the most relevant techniques uncovered in our investigation. Our next milestone shall be investigation of the most promising Machine Learning and AI techniques that may be applicable to the problem at hand, and which are most suitable for the data set to be generated. The deliverable shall be a report summarizing our finding and PPT presentation of some of the most relevant techniques. The anticipated delivery date is August 30, 2017.

PLANNED ACTIVITIES: The research team has regular weekly or bi-weekly meetings going over the latest finding and establishing the next steps and personnel assignments. Our planned activities for the next few months are: (1) Continue and complete the literature search by expected delivery date. (2) Continue and complete the machine learning and AI research by expected delivery date.

PROJECT PERSONNEL: Dr. Fereydoun Daneshgaran.

c) Investigating the effect of recycled fibers on the properties of the self-compacting sustainable geopolymer concrete for underground transportation infrastructure applications

SUMMARY: Over the past three decades, the use of sustainable cementitious materials has been advanced and the application of waste materials in cement-based materials has attracted particular attention. However, the mechanical properties, durability and strength of this type of concrete have not been extensively evaluated as compared to conventional mixes. The objectives of this research are: (1) Improve mechanical properties of SCC geopolymer concrete. (2) Reduce the rate of drying shrinkage and width of cracks. (3) Use recycled fibers to improve the properties of fresh and hardened concrete (e.g. steel fiber recovered from waste tires). (4) Develop analytical relationships to predict the mechanical properties. (5) Investigate the application of fiber-reinforced SCC geopolymer concrete in underground transportation infrastructures. This research topic falls under the category “Investigation of new sustainable and high-performance materials for UTI”. The results of this research could help improve the durability and extending the life of underground transportation infrastructures by utilizing the sustainable concrete materials that improves the workability and durability of the final product.

PROJECT STATUS: Work is in progress in Phase I (Documentation and Information Search).

MILESTONE ACCOMPLISHMENTS: Official start date was May 01, 2017 (due to the timing of subcontract to Cal State LA).

PLANNED ACTIVITIES: Work will continue with the information search and documentation phase. Work will also continue to prepare the detailed plan for Phase II which mainly includes experimental study and laboratory evaluations.

PROJECT PERSONNEL: Dr. Mehran Mazari.

Research at Lehigh University

a) Assessing and improving the resilience of highway and rail tunnels to blast and fire

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

PROJECT STATUS: A thorough literature review on the effects of blast and fire on tunnel liners has been performed and a database containing comprehensive reports, research articles and books has been established. A number of sample TBM tunnel systems design details have been acquired and are being used to develop prototype tunnels. The tunnels are being modeled to examine the thermal and pressure distribution along the tunnel corridor as a result of fire and blast demands. This project will leverage current state-of-practice design basis approaches, existing experimental data, and high-fidelity computational modeling to develop a semi-empirical framework for efficiently calculating the spatial contour and time history of fire and blast effects on the tunnel surfaces. Preliminary discussion on the tasks was conducted with Hawaii Department of Transportation on April 19, 2017 to present the ideas under investigation by the team and to understand the needs of HDOT. Similar discussions are being arranged with Pennsylvania Department of Transportation.

MILESTONE ACCOMPLISHMENTS AND DATES: (1) Literature review and database - May/01/2017. (2) Establishment of tunnel prototypes - June/01/2017.

PLANNED ACTIVITIES: (1) Development of numerical models of tunnel prototypes. (2) Comparison of numerical models with design basis approaches and existing experimental data. (3) Evaluation of tunnels subject to varying thermal demands. (4) Evaluation of tunnels subject to various blast demands. (5) Development of “intermediate” models for spatial and temporal distributions of hazard demands on the tunnel structure.

PROJECT PERSONNEL: Dr. Spencer Quiel and Dr. Clay Naito.

b) Development of a blast and fire resistant structural tunnel liner

SUMMARY: This project will develop a new structural design strategies for mitigation of blast and fire hazards in tunnels. A novel precast segmental liner will be designed for efficient installation and replacement. The scope of demands to be considered will be determined through preliminary analytical evaluations of a set of tunnel types subject to a range of demands (i.e., small/large Improvised explosive device, vehicle fire / fuel transport vehicle fire). Preliminary designs developed based on first principles and current state of the art will be numerically evaluated under the range of load expected. Numerical models will be verified using case study data. The designs will be refined using parametric evaluations. Preliminary experimental investigation of the prototype liner will be conducted to verify resistance to close in blast and fire exposure. Testing will be conducted at facilities available at Lehigh University and Colorado School of Mines. Based on preliminary results, designs may be altered to enhance performance,

and final verifications will be experimentally conducted. Cost and construction efficiencies will be incorporated during the development phases

PROJECT STATUS: A thorough literature review on the effects of blast and fire to typical tunnel lining structures has been performed and a database containing comprehensive reports, research articles and books has been established. The behavior of concrete lining under fire conditions is being investigated experimentally and numerically. The numerical models that describe coupled heat and moisture transfer within concrete tunnel linings are being developed with the aid of high fidelity modeling; COMSOL is employed for the coupled heat and moisture transfer analysis and FDS is used for fire demand estimates. An experimental program is being developed to allow for examination of concrete lining segments. The tests will include variables specifically important to tunnel lining exposed to high temperature. This includes but is not limited to water cement ratio, aggregate type, rebar density, cover, initially applied axial force, and the magnitude of restraint to thermal expansion. Test methods for measuring behavior of tunnel linings to blast are being established. LS-DYNA is being employed to determine blast demand estimates. The numerical results will be used to assess if blast evaluation can be conducted using impact hammers or if full scale detonations are necessary to understand the performance of various panel details and constituents. Experimental tests will focus on shock-induced cracking and spall produced by air-blast on concrete tunnel liners with grout, soil, and/or rock substrate. Preliminary discussion on the tasks was conducted with Hawaii Department of Transportation on April 19, 2017 to present the ideas under investigation by the team and to understand the needs of HDOT. Similar discussions are being arranged with Pennsylvania Department of Transportation.

MILESTONE ACCOMPLISHMENTS AND DATES: (1) Literature review and database- May/01/2017. (2) Fire test matrix - June/01/2017. (3) Initiate numerical modeling of thermal effects - June/15/2017.

PLANNED ACTIVITIES: (1) Design and fabricate fire testing fixture. (2) Fabricate and test panels subject to fire demands. (3) Initiate numerical modeling of panels. (4) Fabricate and test panels using impact hammer or shock tube. (5) Develop preliminary assessment methods for structural damage due to blast and fire.

PROJECT PERSONNEL: Dr. Clay Naito and Dr. Spencer Quiel.

1.2.2 Student Activities

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

a) Six graduate students and three undergraduate students have been hired at CSM, CSULA and Lehigh, and are now working on research projects funded by UTC-UTI. One of the CSM undergraduate students will continue to the MS in Geophysics in Fall 2017. Lehigh recruited one Ph.D. student from the University of Pittsburgh, an undergraduate student from Lehigh University who will go on to pursue his M.Sc. degree at Lehigh, and a post-doctoral researcher who recently completed his Ph.D. from Auburn University.

b) Nine CSM students attended the Rapid Excavation and Tunneling Conference in San Diego in June 4-7, 2017.

c) 17 CSM students attended a field trip on March 16-17, 2017 to visit three tunnel projects in Seattle, WA (Fig. 4).

d) Dr. Priscilla Nelson, UTC-UTI Associate Director for Education, Workforce Development and Diversity, participated in "*Girls Lead the Way*" recruitment event in Denver, CO.

Fig. 4: CSM students on a field trip to visit tunnel projects in Seattle, WA.

1.2.3 Outreach activities

a) UTC-UTI is now a full member of the Council of University Transportation Centers (CUTC).

b) UTC-UTI is now completing the planning and organization of its *First Symposium on Underground Transportation Infrastructure* to be held on September 21 and 22 at Colorado School of Mines. The theme of the First UTC-UTI Symposium is on the "*Challenges and Opportunities for Underground Transportation Infrastructure in the US*." The goal of the symposium is to identify research needs and opportunities. The symposium will draw participants from the industry, government agencies and institutions and the academe, and will highlight presentations from leading experts in the field.

c) UTC-UTI co-hosted a short course on "*Underground Grouting and Ground Improvement*" held on May 1–5, 2017 at Colorado School of Mines. The short course had 111 participants including 37 speakers and 20 CSM students.

d) PIs from UTC-UTI met several times with State DOTs and industrial representatives to discuss potential areas of research collaboration (please Section 3.2 below).

e) UTC-UTI sponsored/co-sponsored seminars related to underground transportation infrastructure. The following seminars were widely attended by CSM faculty and students and were presented mainly by industry practitioners:

"*Large-Scale Triaxial Testing –Application to a Subway Tunnel in Gravelly Material*" - Ramón Verdugo, President, CMGI, and Adjunct Professor, University of Chile.

"*Lucky Friday #4 Shaft: Design and Evolution*" - David Berberick, Senior Project Manager, Hecla Ltd.

"*Thimble Shoal Tunnel Project*" – Collin Lawrence, Global Tunnel Practice Leader and Executive Vice President, Mott McDonald.

"I-70 *Eisenhower-Johnson Memorial Tunnel Fixed Fire Suppression System: A Project Case History*" – James Carroll, West Coast Engineering Manager, ILF Consultants.

"*Michigan Ditch Landslide and Tunnel: A New Tunnel and Unique Delivery System*" – Nate Soule, Vice President and Founder of Lithos Engineering.

"*Tunneling for Sustainable Growth*" – Enrique Fernandez, Head Tunneling Technical Director, Dragados S.A.

1.2.4 Leveraging UTC-UTI funds

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

a) An REU (Research Experiences for Undergraduates) Site proposal, based on research being carried out by UTC-UTI, is now being completed jointly by CSM, CSULA and Lehigh, and will be submitted to the National Science Foundation in August 2017. The aim is to provide support for four to five undergraduate students per year each at CSM, CSULA and Lehigh to join UTC-UTI research activities during summers.

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

c) CSM's Earth Mechanics Institute (EMI) will allow free use of EMI laboratory facilities for two research projects funded by UTC-UTI. Estimated cost match is $65,000.

d) IET Waterjet Foundation is providing $3,500 support for travel.

e) MapTek is contributing licenses for the software I-Site Studio and Vulcan. Estimated annual cost-match is $120,600 for I-site and $174,850 and Vulcan. I-Site and Vulcan are powerful 3D subsurface modeling tools that will be used for 3D underground tunnel modeling.

f) Ajou University, South Korea, has committed to providing data on metro subway construction projects in Seoul, South Korea, for an estimated in-kind cost match of $500,000.

g) Tongji University, China, has committed to providing data on tunnel construction projects in China for and estimated in-kind cost match of $250,000.

h) Jay Dee Contractors and Sound Transit have provided cross passage construction data related to the Northlink Extension Project in Seattle, Washington, for an estimated in-kind cost match of $100,000.

i) Equipment required for thermal testing will be provided by Lehigh University via faculty startup fund for Dr. Stephen Quiel.

j) Discussions with different State DOTs and tunneling/construction companies are in progress on collaborative projects that State DOTs and industry can potentially co-fund or cost-match (please see Section 3.2 below).

1.2.5 Faculty and researcher accomplishments

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

a) Dr. Marte Gutierrez, UTC-UTI Director, received the *2017 Applied Rock Mechanics Research Award* from the American Rock Mechanics Association.

b) Dr. Mike Mooney, UTC-UTI Deputy Director, was Keynote Lecturer in two conferences, and Invited Lecturer in three seminars and conferences, all related to tunneling.

c) Dr. Priscilla Nelson, UTC-UTI Associate Director for Education, Workforce Development and Diversity, was identified as one of the "*Faces of Innovation*" and interviewed for video on innovation by NTTi3 (San Francisco, CA). She organized the "Summit on Mine Closure" at Colorado School of Mines, and continued to serve in the US Committee on Geological and Geotechnical Engineering, Division on Earth and Life Studies, National Academies, and (as Chair) in the Mine Safety and Health Research Advisory Committee.

d) Dr. Hugh Miller, UTC-UTI co-PI, had received several prestigious industry awards including the *American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) Honorary Member Award*, and the *Society for Mining, Metallurgy & Exploration (SME) SME-AIME Mineral Industry Education Awar*d. He has also given invited technical presentations to the SME Foundation-Reno Section, and the National Defense University, Eisenhower School, and has organized and chaired a session at the 2017 SME Annual Conference on Academic Advancement for New Faculty.

e) Dr. Wendy Zhou, UTC-UTI co-PI, has been *appointed as Dean of Graduate Studies* of Colorado School of Mines.

f) Dr. Gabriel Walton, UTC-UTI co-PI, was *the runner-up for the 2017 International Rock Mechanics Society Rocha Medal*. He also gave a keynote lecture at the 6th International Bridge and Tunnel Technology Conference in Shanghai, and was in the Organizing Committee for the 51st U.S. Rock Mechanics/Geomechanics Symposium.

g) Dr. Stephen Quiel, UTC-UTI co-PI, was *appointed P.C. Rossin Assistant Professor* at Lehigh University. He also gave an invited presentation at the National Institute of Standards and Technology, and organized and chaired sessions at the 2017 ASCE/SEI Structures Congress.

h) Dr. Eunhye Kim, UTC-UTI co-PI, was invited to give presentations at Ajou University and Seoul National University in South Korea.

i) Dr. Simon Heru Prassetyo, UTC-UTI Research Associate, received the *Spring 2017 Best Civil and Environmental Ph.D. Dissertation Award* from Colorado School of Mines.

2. PRODUCTS

2.1 Publications, conference papers, and presentations

Book Chapter:

a) Nelson, P.P. "Societal Benefits," Chapter 2 in The History of Tunneling in the United States published by the Society for Mining, Metallurgy & Exploration Inc., 2017.

Journal Publications:

As the Center has just started, there were no journal publications from the Center for the reporting period.

Conference Papers and Presentations:

a) Valenzuela, Y.B., Rosas, S.R., Mazari, M., Risse, M., and Rodriguez-Nikl, T., "Resilience of Road Infrastructure in Response to Extreme Weather Events," American Society of Civil Engineers (ASCE), International Conference on Sustainable Infrastructure, New York City, NY, 2017.

b) Prassetyo, S.H. and Gutierrez, M., "Efficient Sequential Coupling Technique for the Simulation of Hydro-Mechanical Interaction in Rock Engineering," Proc. 51th US Rock Mechanics/Geomechanics Symposium, Houston, Texas, June 25-28, 2017.

c) Yu, H., Mooney, M.A. and Bezuijen, A., "Chamber Pressure Modeling for Earth Pressure Balance Tunnel Boring Machines: A Tri-Phase Simulation Framework," Proc. 9th Intl. Symp. Geotechnical Aspects of Underground Construction in Soft Ground, IS-Sao Paulo, April 4-5, 2017.

d) Mooney, M.A., Wu, Y., Parikh, D. and Mori, L., "EPB Granular Soil Conditioning under Pressure," Keynote Paper. Proc. 9th Intl. Symp. Geotechnical Aspects of Underground Construction in Soft Ground, IS-Sao Paulo, April 4-5, 2017.

e) Buckley, J., Mooney, M.A., Toohey, N., Planes, T., Alavi, E. and DiPonio, M., "Cutterhead Protection in a Boulder Field using Real Time Vibration Monitoring," Proc. Rapid Excavation and Tunneling, San Diego, CA. June 4-7, 2017, 15 pp.

f) Mooney, M.A., Tilton, N., Parikh, D. and Wu, Y., "EPB TBM Foam Generation," Proc. Rapid Excavation and Tunneling, San Diego, CA. June 4-7, 2017, 13 pp.

g) Grasmick, JG. and Mooney, M.A., "A Probabilistic Approach for Predicting Settlement due to Tunneling in Spatially Varying Glacial Till," Proc. 6th Intl. Symp. on Geotechnical Safety and Risk, Denver, June 4-7, 2017.

h) Kim. E. "Excellence in Underground Construction and Tunneling," presentation given at Ajou University, June 29, 2017.

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

a) UTC-UTI has now a fully functional Center website at: http://underground.mines.edu/utc-uti

b) UTC-UTI has now a webpage for archiving and dissemination hosted by Zenodo at: https://zenodo.org/communities/utc-uti/

2.3 Technologies or techniques

Nothing to report for the reporting period.

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 have given *presentations in the UTC-UTI sponsored/co-sponsored seminar series*:

- CMGI Ltd (Santiago, Chile)
- Hecla Ltd. (Coeur d'Alene, ID)
- Mott McDonald (Millburn, NJ)
- ILF Consultants (Westminster, CO)
- Lithos Engineering (Lakewood, CO)
- Dragados S.A. (Madrid, Spain and Lawrence, NY)

b) Representatives from the following organizations have agreed to becomes *members of the UTC-UTI Advisory Board*:

- Colorado DOT (Denver, CO)
- Federal Highway Administration (Washington, DC)
- Mott MacDonald (Millburn, NJ)
- Council of University Transportation Centers (Washington, DC)
- Arup (New York, NY)
- Ajou University (Seoul, South Korea)
- Penn DOT (Harrisburg, PA)
- WSP/Parsons Brinckerhof (Chicago, IL and Washington, DC)
- Tongji University, China (Shanghai, China)

c) The following organizations have committed to *provide cash or in-kind cost-match to UTC-UTI projects*:

- RAMAX LLC (Lakewood, CO)
- CSM Earth Mechanics Institute (Golden, CO)
- IET Waterjet Foundation (London, UK)
- MapTek (Golden, CO)
- Ajou University (Seoul, South Korea)
- Tongji University (Shanghai, China)
- Jay Dee Contractors (Livonia, MI and Lakewood, CO)

- Sound Transit (Seattle, WA)

d) Representatives from the following organizations are *assisting in the organization of the First UTC-UTI Symposium* to be held in September 21-22, 2017:

- Federal Highway Administration (Washington, DC)
- C.W. Felice, LLC (Kirkland, WA)
- Pennsylvania DOT (Harrisburg, PA)

3.2 Have other collaborators or contacts been involved?

1) CSULA has been in contact with the LA Metro Purple Line Project (Bill Edgerton, Construction Manager) for potential access to TBM and construction-related data from this construction. There will be a follow-up meeting in July for more in-depth discussions.

2) Lehigh University is leveraging UTC-UTI funds to expand initial studies on the thermal response of high strength reinforcements which can be utilized in the studies underway as part of the UTC-UTI. The Lehigh team met with Jason Lien of Encon United and the chief precast engineer for the Seattle State Route 99 Tunnel Project. Discussion was focused on issues involved in the tunnel construction, and section drawings and details for the precast tunnel liner system were procured. Another meeting was held with HDOT (Wayne Kawahara and others) and FHWA (Domingo Galicinao). Discussion was focused on Lehigh's UTC-UTI projects and HDOT tunnel needs. Oahu, HI, has three main tunnel segments that have a high traffic demand. Research needs are limited and focus more on maintenance issues that arise in the high humidity and salt air environment. Additionally, a phone meeting was held with PennDOT (Tom Macioce, Chief Bridge Engineer) to get contacts for tunnel efforts in Pennsylvania. Meetings will be arranged with Louis Ruzzi, District 11 Bridge Engineer and Chair of AASHTO T-20, and Jim Stump, Pennsylvania Turnpike Chief Bridge Engineer.

3) CSM held continuous discussions with Colorado DOT on co-funding or cost-matching of research projects. The following is a tentative list of potential research projects that can be collaboratively carried by out UTC-UTI and CDOT:

   a) *Mobile LiDAR and Thermal Image Analysis of Tunnels* (in concert with SHRP2 NDT). Fit with UTC-UTI Research Area 1 - Condition monitoring, remote sensing and use of GPS. Scope of work: TBA. Deliverable: TBA.

   b) *Asset Management of Shotcrete Liner Support*. Fit with UTC-UTI Research Area 2 – Asset management and performance management. Scope of work: Develop framework for asset management of shotcrete lining support throughout CDOT, e.g., maintenance (washing, sealing, etc.), and how to extend life. Deliverable: Report including framework in a form convenient for CDOT personnel, and an implementation plan.

   c) *Monitoring Movement of Existing Tunnels*. Fit with UTC-UTI Research Area 1 - Condition monitoring, remote sensing and use of GPS. Scope of work: Develop and implement an active monitoring system for one or two tunnels that have exhibited cracking and warrants review (i.e., condition state 4). Deliverables: (1) A report on the design and expected performance of monitoring system. (2) Installed monitoring system on one or two CDOT tunnels. (3) A report of tunnel movement over a TBD monitoring period and analysis of the performance of the monitoring system.

   d) *Asset Management of Cast in Place Concrete Liner*. Fit with UTC-UTI Research Area 2 – Asset management and performance management. Scope of work: Develop framework for asset

management of cast-in-place concrete liner support throughout CDOT, e.g., how to economically bring deteriorated concrete back to condition state 2 (e.g., suturing techniques, can pavement methods be applied, etc.), how to prioritize use of funding, etc. Deliverable: Report including framework in form that CDOT personnel can follow and implementation plan.

e) *Improving Construction Quality and Cost through Monitoring (related to Central 70)*. Fit with UTC-UTI Research Area 2 – Asset management and performance management, and Research Area 3 – New materials and technologies. Scope of work: Using active CDOT projects (ideal project is Central 70), improve the implementation and use of construction monitoring (including geotechnical and structural monitoring, and related technologies such as 4D CAD) to improve construction quality, time and cost, and to manage risk (e.g., foresee and mitigate problems). For an active project such as Central 70, the research team would work with CDOT and in parallel with contractor to implement the study. The research team would be given access to project information and the monitoring data to perform the study. The study would be framed so as not to adversely impact the project. Deliverables: (1) Real time reporting of construction monitoring to CDOT throughout the project. (2) Report of study features and how they could be used to improve construction. (3) Recommendations for implementation on future CDOT projects.

f) *New Materials for Fire Protection*. Fit with UTC-UTI Research Area 3 – New materials and technologies. Scope of work: Examine current and emerging materials (and approaches) used in tunnel lining fire protection, e.g., alternatives to tiles, replacement of air gap, possibility of spray-on material, etc. Deliverable: Synthesis report.

g) *Tunnel Crossover Retrofitting*. Fit with UTC-UTI Research Area 2 – Asset management and performance management and Area 3 – New materials and technologies. Scope of work: TBA. Deliverable: TBA.

h) *Tunnel Boring Machine (TBM) Feasibility Study on Mining Techniques for a Potential Third Bore of Eisenhower-Johnson Memorial Tunnel*. Fit with UTC-UTI Research Area 3 – New materials and technologies. Scope of work: Perform an examination of the feasibility of TBM, roadheader, drill and blast, and any other new techniques (water jet, etc.) specifically for the 3rd bore of the Eisenhower-Johnson Memorial tunnel. Deliverable: Feasibility report.

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 therefore 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. It is envisioned that 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. As UTC-UTI has just started, work is still at the early stages of development towards the goals of providing impact on the areas covered by the Center.

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?
Six graduate students, three undergraduate students and one post-doc were hired at CSM, CSULA and Lehigh and are currently supported by UTC-UTI through research assistantships. In addition, at CSULA, 11 undergraduate and six graduates, who were unsupported by UTC-UTI, worked on related research with CSULA faculty UTC-UTI also has held outreach and recruiting initiatives aimed at encouraging undergraduate students to pursue advanced degrees in Underground Transportation Infrastructure.

4.4 What is the impact on physical, institutional, and information resources at the university or other partner institutions?

Results from UTC-UTI are being widely disseminated and archived for long-term access using Zenodo, which is a publicly available data repository. Archived research results can help support future research in the area of Underground Transportation Infrastructure at partner institutions and the academe in general, and to promote technology transfer to the industry. Links to the archived results are actively promoted through our Center webpage.

4.5 What is the impact on technology transfer?

UTC-UTI interacts with industrial and state DOT partners to provide mechanisms for stimulating technology transfer, and turning research results directly into technological innovation. Technology transfer is being carried out in three ways: (1) working with various components of the underground transportation industry for direct technology transfer, e.g., through industry-funded, co-funded or cost-matched research; (2) sharing of innovations via continuing education, seminars and workshops, and (3) dissemination through publications of research in journals and conference proceedings, reports, and design manuals, and through our archiving and dissemination website at Zenodo. One activity from this reporting period which, illustrates UTC-UTI's strong commitment to technology transfer, was the short course on "Underground Grouting and Ground Improvement" which was well attended by industry practitioners and CSM students. UTC-UTI PIs have also been very active in pursuing potential collaborative projects that are of value to the industry and DOTs.

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.

4. CHANGES/PROBLEMS

The main challenge faced by UTC-UTI during this first reporting period was in the recruiting of Post-doc Research Associates and its first cohort of Graduate Research Assistants. It appears that, due to the strong economy and high demand in the construction industry, students prefer to work instead of pursuing graduate degrees. Due to the shortage of research personnel, the Center budget for Year 1 will probably not be fully spent and will have to be re-allocated to Year 2. Increased efforts will be made to fill up Center research positions in the next reporting periods.