Quarterly Progress and Performance Indicators Report:
Project Number and Title: 3.12—Lateral Loading of Unreinforced Rigid Elements and Basal Stability of Columns Supported Systems
Research Area: Geotechnical Infrastructure Engineering
PI: *Aaron Gallant, University of Maine*
Co-PI(s): *N/A*
Reporting Period: *7/1/2022-9/30/2022*
Submission Date: *9/29/2022*

******IMPORTANT: Please fill out each section fully and reply with N/A for questions/sections with nothing to report. For ease of reporting to the USDOT, please do not remove, or change the order of, any sections/text. You may remove/add each rows in tables as needed. Thank you! ******
The report is due on the last day of the reporting period in .doc format to tidc@maine.edu.

Overview:

Phase 1: The following list contains a brief highlight of the activities performed during the quaternary report 03/2021-7/2021. These activities conclude the first phase of this project that is refer in Table 1 as Task 1.

- A new definition of factor of safety (FS), that in addition to the development of a passive wedge, also consider mobilization of shear strength of soil beneath an embankment slope or Mechanically Stabilized Earth (MSE) wall was considered to address the failure mechanism due to the lateral spreading that is more catastrophic.

- A parametric study of MSE walls supported on rigid validated that the column fracturing is a consequence of lateral spreading, and it does not necessarily exacerbate the issue or trigger basal instability — similar conclusion was found for the embankment loading case. Furthermore, it was reaffirmed that a stiff surficial layer is a critical component of lateral stability and confinement at the toe.

Phase 2: The following list contains a brief highlight of the activities performed during this quaternary report. These activities were focused on the Task 2, which consists of developing an analytical methodology to evaluate the factor of safety against lateral spreading of Column-supported Embankments (CSE).

- An analytical model to compute the Factor of Safety against lateral spreading of Column-Supported Embankments has been developed. This model is capable to predict the Factor of Safety for different crust thicknesses, undrained shear strength of the crust and weaker material, embankment slopes, fill heights, and column geometries.
- A methodology that relates the factor of safety of CSE against basal stability with the stability number has been proposed with the goal of producing a simplify approach to check the factor of safety for different column and subsoil conditions. Several stiffness factors that link the column geometry and the subsoil conditions have been analyzed and compared with the lateral deformation at the toe of the CSE, resulting in a chart to evaluate the lateral deformation of the system.

Meeting the Overarching Goals of the Project:

Phase 1: These activities helped to meet the goal of phase I, due to the following reasons:

- The new factor of safety gave more accurate representation of the global stability of a column-supported (CS) system. Thus, the consequences of column fracturing were related to this factor of safety.

- The parametric study showed several conditions where the FS against global stability meet the actual design criterion (i.e., FS greater than 1.3 for undrained and 1.5 for drained scenario), and column fracturing occurred before reaching the final fill height. This implied that some degree of column fracturing can be tolerated. It was also found that fracturing does not necessarily exacerbate the lateral spreading or trigger basal instability. The importance of the presence of a stiff surficial layer is also highlighted by the parametric study.

Phase 2: These activities helped to meet the goal of phase II, due to the following reasons:

- The new analytical model for lateral spreading compares well with the computed results obtained with Plaxis 3D using the Strength Reduction Method (SRM). This new model is intended to be use among practitioners to check the lateral spreading and basal stability requirements of the CSE.

Aside from the lateral spreading the basal stability is also analyzed using the Strength Reduction Method and it is compared with the stability number. Lateral deformations were compared with the system stiffness factor.

Accomplishments:

Phase 1:
The global objective of the phase I (related to task 1 in Table 1:) was achieved and it is presented as follows:

- Task 1: A numerical study performed on both Embankments and MSE walls supported on rigid inclusions demonstrated that some degree of column fracturing can be tolerable if subsurface conditions provide adequate confinement, that comes mainly for the passive resistance of a stiff surficial layer (either a dense fill or a highly overconsolidated clay) --- typically found in the subsurface conditions of geotechnical projects.

The achieved subgoals of the Phase I are presented as follows:

- Task 1.1: The subgrade response of full scale geosynthetic reinforcement column-supported embankments at the Council Bluff interchange system (CBIS) determined that downdrag appreciably reduced stress in soil above the neutral plan and the crust material at the shallow soils effectively served as a subsurface load transform platform (LTP).

- Task 1.2: The discrete-crack method was adopted to simulate the cessation of tensile-resistance at the columns. This method consists of introducing interface elements every meter along all columns at depth with a predefined orientation (in this case horizontal). Once the column stresses are equal or greater than the rupture modulus of the concrete, the crack is activated, allowing the energy release due to the fracture propagation.

- Task 1.3: Observed lateral and vertical deformations were in excellent agreement with the predicted deformations via numerical analysis. This agreement was achieved, in part, through calibration of the laboratory test (i.e., undrained triaxial compression tests and 1D consolidations tests), the characterization of subsurface layering, and the interpretation of the preconsolidation profile via correlations with the cone penetration test (CPT) and 1D consolidation tests.

- Task 1.4: A parametric study was carried out in column-supported embankments and MSE walls to link the degree of lateral spreading with column fracturing and the factor of safety against basal stability. The parametric study was designed based on a collection of documented CS systems, maintaining the subsoil condition, and column geometry within realistic designs. In both loading scenarios (i.e., embankments and MSE walls), it was found that the greatest influence on lateral deformations and computed factors of safety were the thickness of a stiff surficial layer and the drainage condition.

Phase 2: The achieved subgoals of the Phase II are presented as follows:

- Task 2.1: A literature review of different methodologies to obtain FS for CSE was performed. Currently, there are two analytical models for column supported embankments that predict the factor of safety against basal stability, however the inclusions are made of gravel (low stiffness columns). Both methodologies used a composite section between the columns and the soil matrix to develop the model. It is not possible to apply the same procedure to the high modulus columns (concrete), because conservative factor of safety would be obtained.

- Task 2.2: Several foundation conditions for a constant column geometry were studied using finite element method (Plaxis 3D) in where the FS of safety were obtained using the Strength reduction method. The undrained shear strength of the weaker material and the crust thickness were varied to analyze the different failure modes and compare with the analytical model (Task 2.3).

- Task 2.3: The factor of safety using the analytical model agreed well with the numerical analysis. However, there are some cases where different failure modes were found, for example, when the crust was thin (about 0.5 m) or the undrained shear strength of the softer material is very low (about 5 kPa). For these cases, the factors of safety for the analytical model did not agree well with the numerical analysis (difference greater than 10%).

- Task 2.3: A new methodology has been developed that overcome the assumption of the failure surface passing only through the crust. The methodology is intended to capture the magnitude of the factor of safety and location of the failure surface. The methodology accounts for load transfer mechanisms (arching and downdrag) and is being compared with 3D finite element models to validate the simplified procedure that is more computationally efficient.

- Task 2.3: A better understanding of the soil stresses at the surface and the soil-column interaction at depth allowed to better understand the limitations of the analytical factor of safety when comparing with the numerical solution. A new model is needed to better represent the stresses at the soil.

Task 2.3: The parametric study allowed to study the influence of different subsoil conditions and column geometries. Then, the weight of each parameter and its influence is represented in the stability number.

- A good correlation was found when comparing the factor of safety with the normalized the lateral with the soil thickness. The necessity of develop the stability number is in question.

Phase 3: The achieved subgoals of the Phase II are presented as follows:

- Task 3.1: Several system stiffnesses were defined based on dimensionless physical relations and compared with the lateral deformations at the toe. Finally a simplify chart is proposed to quickly check the expected lateral deformation under a specific column geometry and subsoil conditions.

<u>Task Progress and Budget:</u>

A detailed project schedule is presented in Table 1.

Table 1: Task Progress			
Task Number: Title	**Start Date**	**End Date**	**% Complete**
Phase I			
Task 1. Assessing the influence of column fracturing in the basal stability of Column-supported systems	06/2018	06/2021	100%
Task 1.1: Assess the stresses in the subsoil	06/2018	06/2019	100%
Task 1.2: Establish a numerical approach to account for fracture in basal stability.	06/2019	09/2019	100%
Task 1.3: Calibrate models with field measurements that include lateral and vertical deformations.	06/2019	12/2020	100%
Task 1.4: Perform parametric study for fill embankments and MSE walls.	01/2020	06/2021	100%
Phase II			
Task 2: Assessing the Factor of Safety (FS)	09/2021	11/2021	
Task 2.1: Literature review of different methodologies to obtain FS	9/2021	10/2021	100%
Task 2.2: Investigating the effect of columns details and foundations materials on the FS via parametric study	10/2021	10/2021	100%
Task 2.3: Relating the FS to the studied variables in Task 2.2 to produce a simplify approach to determine the FS for different conditions	10/2021	11/2021	100%
Task 3: Linking the FS to Lateral Spreading	11/2021	01/2021	100%
Task 3.1: Creating several system stiffness definitions based on dimensionless physical relations or another method.	11/2021	12/2021	100%
Task 3.2: Extending the parametric study (in Task 2.3) to validate and find the best system stiffness parameter	12/2021	01/2022	100%
Task 4: Validating the methodology	01/2022	06/2022	0%

Task 4.1: Compare the predicted versus the calculated lateral deformation using the proposed methodology with the existing field case inventory	01/2022	02/2022	0%
Task 4.2: Analyze the subsoil conditions and column geometry for new data provided by the Deep Foundation Institute (DFI) and the existing inventory	02/2022	06/2022	0%
Phase 1: Assessing the influence of column fracturing in the basal stability of Column-supported systems	06/2018	09/2021	100%
Phase 2: Creating a simplified methodology to evaluate the factor of safety for Basal Stability and the magnitude of lateral spreading for Column supported systems	09/2021	6/2022	90%
Phase 3: Performing a probabilistic analysis of basal stability of column support embankments using the collocation method to study the sensitivity of the column geometry and subsoil conditions	06/2022	9/2022	0%
Phase 4: Analyzing the final failure state of a Column-supported system using the Material Point Method (MPM).	9/2022	12/2022	0%

Table 2: Budget Progress		
Project Budget	**Spend – Project to Date**	**% Project to Date (include the date)**
Phase 1: $33,380		
Phase 2: $46,146		

Is your Research Project Applied or Advanced?

☒ **Applied** (*The systematic study to gain knowledge or understanding necessary for determining the means by which a recognized and specific need may be met.)*

☐ **Advanced** *(An intermediate research effort between basic research and applied research. This study bridges basic (study to understand fundamental aspects of phenomena without specific applications in mind) and applied research and includes transformative change rather than incremental advances. The investigation into the use of basic research results to an area of application without a specific problem to resolve.)*

Professional Development/Training Opportunities:

Describe any opportunities for training/professional development that have been provided. Did you provide a training to a State DOT/AOT or industry organization? What was the training? When was it offered? How many people attended? Did you meet with a State DOT/AOT or industry organization to inform them of your findings and how these findings could help their organization? When? How many attended the meeting?

Technology Transfer:

*Complete all of the tables below and provide additional information where requested. Please provide ALL requested information as this is one of the most important sections for reporting to the USDOT. **ONLY provide information relevant to this reporting period.***

Use the table below to complete information about conference sessions, workshops, webinars, seminars, or other events you led/attended where you shared findings as a result of the work you conducted on this project:

Table 3: Presentations at Conferences, Workshops, Seminars, and Other Events					
Type	**Title**	**Citation**	**Event**	**Location**	**Date(s)**
Conference	2020 TIDC annual Conference	N/A	2020 TIDC annual Conference	University of Maine	August 12,2020
Conference	*Special recognition award for the 2021 DFI Educations Trust's Young Professor Paper	N/A	45th Annual Conference on Deep Foundations	Online	October 27, 2020
Conference	1st place of TIDC 2021 Student Poster Contest	N/A	2021 Student Poster Contest	Online	December 1, 2021
Presentation	DFI's Ground Improvement Committee Mid Year Meeting 2022	N/A	DFI Mid Year Meeting	Online	April, 7, 2022
Presentation	Committee's mid-year Virtual Meeting 2022	N/A	Transportation Earth Works Committee	Online	July, 18, 2022

Use the table below to report any publications, technical reports, peer-reviewed articles, newspaper articles referencing your work, graduate papers, dissertations, etc. written as a result of the work you conducted on this project. Please list only completed items and exclude work in progress.

Table 4: Publications and Submitted Papers and Reports				
Type	**Title**	**Citation**	**Date**	**Status**
Peer reviewed Journal	Field Observations and Analysis of the Subgrade Response beneath GRCS Embankments at the Council Bluffs Interchange System	Gallant, Aaron, Ehab Shatnawi, and Danilo Botero-Lopez. 2019. "Field Observations and Analysis of the Subgrade Response beneath GRCS Embankments at the Council Bluffs Interchange System." Journal of Geotechnical and Geoenviromental Engineering.	2020	Accepted

Peer reviewed Journal	Lateral Spreading of Embankments supported on Fractured Unreinforced high-modulus columns over Soft Soil	Gallant, Aaron, and Danilo Botero-Lopez. 2019. "Lateral Spreading of Embankments supported on Fractured Unreinforced high-modulus columns over Soft Soil." DFI Journal.	2021	Accepted
Final Report	Lateral Spreading and Basal Stability of Embankments and MSE Walls Supported on Unreinforced High-Modulus Columns	Gallant, Aaron, and Danilo Botero-Lopez. 2019. "Lateral Spreading and Basal Stability of Embankments and MSE Walls Supported on Unreinforced High-Modulus Columns." DFI final report.	2021	Accepted

Answer the following questions (N/A if there is nothing to report):

1. Did you deploy any technology during the reporting period through pilot or demonstration studies as a result of this work? If so, what was the technology? When was it deployed? N/A

2. Was any technology adopted by industry or transportation agencies as a result of this work? If so, what was the technology? When was is adopted? Who adopted the technology? N/A

3. Did findings from this research project result in changing industry or transportation agency practices, decision making, or policies? If so, what was the change? When was the change implemented? Who adopted the change? N/A

4. Were any licenses granted to industry as a result of findings from this work? If so, when? To whom was the license granted? N/A

5. Were any patent applications submitted as a result of findings from this research? If so, please provide a copy of the patent application with your report. N/A

6. Were any industrial contracts awarded base on furthering planned research and development activities as a result of findings from this work? If so, when? How much was awarded? Who awarded the contract? N/A

Fig.1a presents an example of the free body diagram of a Column Supported Embankment of a 5 m high with a column spacing of 2 m assuming a failure surface at z=4 m to calculate the factor of safety against basal stability. The Incremental shear strains obtained using finite element analysis (FEA) is superposed to compared with the analytical solution. Fig 1.b presents the variation of the Factor of safety computed analytically with depth. It also shows the finite element solution which agreed very well. Finally, Fig.1c, presents different assumptions of the factor of safety which gives different values of resistance and loads, the analytical FS is obtained when both load and resistance are the same.

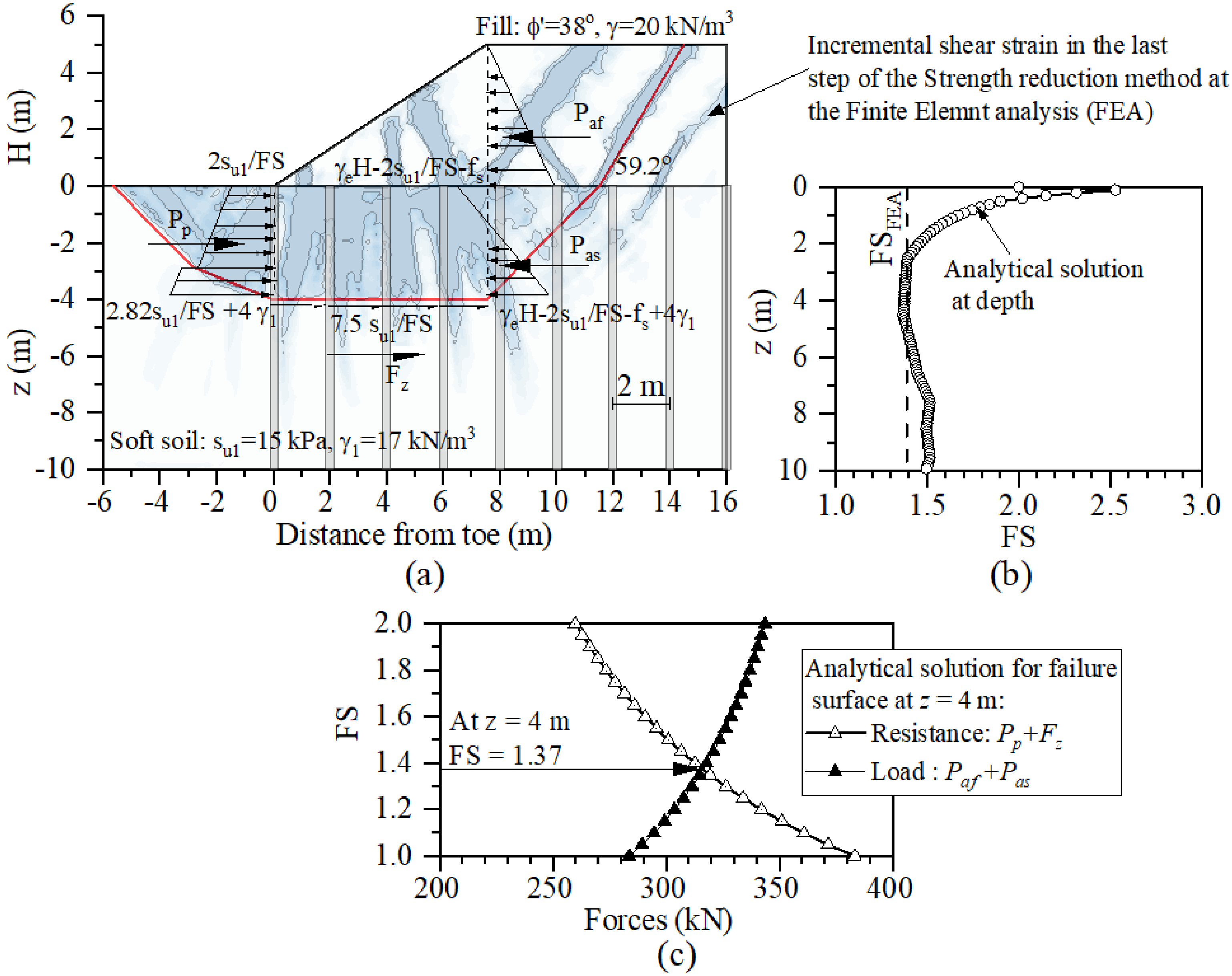

Figure 1. (a) Free body diagram of the forces acting in the CSE including the incremental shear strains obtained by Plaxis 3D of a fill of 5 m high and column spacing equal to 2 m. (b) Analytical solution of the factor of safety against basal stability at depth compared with the Finite Element calculation; (c) Example of the loads and resistance for different assumptions of factor of safety.

Describe any additional activities involving the dissemination of research results not listed above under the following headings:

Outputs:
Definition: Any new or improved process, practice, technology, software, training aid, or other tangible product resulting from research and development activities. They are used to improve the efficiency, effectiveness, and safety of transportation systems. List any outputs accomplished during this reporting period:

- Example: New sensing technology was developed. This technology will…

Outcomes:
Definition: The application of outputs; any changes made to the transportation system, or its regulatory, legislative, or policy framework resulting from research and development activities. List any outcomes accomplished during this reporting period:

- Example: The developed sensing technology was installed in Bridge A in town, state on 1/1/2021. This installation will…

Impacts:
Definition: The effects of the outcomes on the transportation system such as reduced fatalities, decreased capital or operating costs, community impacts, or environmental benefits. The reported impacts from UTCs are used for the assessment of each UTC and to make a case for Federal funding of research and education by demonstrating the impacts that UTC funding has had on technology and education. NOTE: The U.S. DOT uses this information to assess how the research and education programs (a) improve the operation and safety of the transportation system; (b) increase the body of knowledge and technologies; (c) enlarge the pool of people trained to develop knowledge and utilize technologies; and (d) improves the physical, institutional, and information resources that enable people to have access to training and new technologies. List any outcomes accomplished during this reporting period:

- Example: The developed sensing technology's successful deployment resulted in the adoption of the technology by the StateDOT. The technology will be installed in all new bridge installments of this type. This adoption will…

Participants and Collaborators:

*Use the table below to list **all** individuals (compensated or not) who have worked on the project.*

Table 5: Active Principal Investigators, faculty, administrators, and Management Team Members				
Individual Name & Title	**Dates involved**	**Email Address**	**Department**	**Role in Research**
Aaron Gallant, Ph.D, P.E.		aaron.gallant@maine.edu	Civil and environmental Engineering department	Principal investigator (PI)

*Use the table below to list **all** students who have participated in the project during the reporting period. (This includes all paid, unpaid, intern, independent study, or any other student that participated in this project.) **ALL FIELDS ARE REQUIRED.***

Table 6: Student Participants during the reporting period

Student Name	Start Date	End Date	Advisor	Email Address	Level	Major	Funding Source	Role in research
Danilo Botero-Lopez	06/2018		Aaron Gallant		Master	Civil Student	TIDC and DFI	Modeling in Finite Element, analyzing the results, and creating final figures

Use the table below to list any students who worked on this project and graduated or received a certificate during this reporting period. Include information about the student's accepted employment (i.e. the student is now working at MaineDOT) or if they are continuing their students through an advanced degree (list the degree and where they are attending).

Table 7: Students who Graduated During the Reporting Period

Student Name	Degree/Certificate Earned	Graduation/Certification Date	Did the student enter the transportation field or continue another degree at your university?
Danilo Botero-Lopez	Master of Science Civil Engineering	08/21/2020	Join to the Ph.D. program at the University of Maine

Use the table below to list any students that participated in Industrial Internships:

Table 8: Industrial Internships

Student Name	Degree/Certificate Earned	Graduation/Certification Date	Did the student enter the transportation field or continue another degree at your university?
N/A			

*Use the table below to list **organizations** that have been involved as partners on this project and their contribution to the project.*

Table 9: Research Project Collaborators during the reporting period

Organization	Location	Contribution to the Project				
		Financial Support	In-Kind Support	Facilities	Collaborative Research	Personnel Exchanges
Deep Foundations Institute (DFI)-Phase I	Hawthorne, NJ	$33,380				

Jacobs Engineering	Herndon, VA		X			
Deep Foundations Institute (DFI)-Phase II	Hawthorne, NJ	$17,100				

*Use the table below to list **individuals** that have been involved as partners on this project and their contribution to the project.*
***(List your technical champion(s) in this table.** This also includes collaborations within the lead or partner universities who are not already listed as PIs; especially interdepartmental or interdisciplinary collaborations.)*

Table 10: Other Collaborators

Collaborator Name and Title	Contact Information	Organization and Department	Date(s) Involved	Contribution to Research
N/A				

Use the following table to list any transportation related course that were taught or led by researchers associated with this research project:

Table 11: Course List

Course Code	Course Title	Level	University	Professor	Semester	# of Students
N/A						

<u>Changes:</u>

N/A

<u>Planned Activities:</u>

The activities planned for the quaternary (10/1/2021-12/31/2021*)* are listed as follows:

- Finishing the literature review of different methodologies to obtain the Factor of safety against basal stability (FS)
- Investigating the effect of column details and foundation materials on the FS via parametric study
- Producing a simplify approach to calculate the FS

The activities planned for the quaternary (1/1/2022-4/01/2022) are listed as follows:

- Finishing the parametric study for different column spacings and other conditions.
- Linking the factor of safety with the lateral deformation to create the system stiffness factor

The activities planned for the quaternary (4/01/2022-7/1/2022) are listed as follows:

- Comparing the predicted versus the calculated lateral deformation using the proposed methodology with the existing field case inventory
- Extend the study for the drained conditions

The activities planned for the quaternary (6/30/2022-9/1/2022) are listed as follows:

- Continue validating the simplified methodology

The activities planned for the quaternary (9/30/2022-12/1/2022) are listed as follows:

- Continue improving the simplified methodology using a better representation of the soil stresses at the surface and a model to study the interaction soil-column
- Validate the methodology with a field case inventory, in case the data is share by third parties