**<u>Quarterly Progress Report</u>:**
**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):**
**Reporting Period:** *06/2018-12/2019*
**Submission Date:** *31/12/2019*

**<u>Overview:</u> (Please answer each question individually)**

*Provide **BRIEF** overview and summary of activities performed during the reporting period. This summary should be written in lay terms for a general audience to understand. This should not be an extensive write up of findings (those are to be included in the final report), but a high-level overview of the activities conducted during the last three months….*

The ultimate goal of this research is to establish the causes and associated conditions that would lead to a basal instability (i.e. bearing/geotechnical failure) beneath column-supported embankments (CSEs) or mechanically stabilized earth (MSE) walls supported on *unreinforced* rigid elements. For any bearing or basal instability to occur in a fill-scenario, excessive unbalanced stresses must be applied to the native subgrade  Column-support reduces the effective embankment or fill stresses applied to the native subgrade by transferring load to the columns via arching—and in cases where a load transfer pad exists—geosynthetic reinforcement. Therefore, a basal instability may occur if: i.) the area replacement ratio is such that load is not adequately transferred to the columns and subgrades stresses are too great; or ii.) the columns yield structurally *and* subsequently overcome passive resistance provided by the soil—displacing such that there is a cessation in the load transfer mechanisms—causing an increase in applied stress to the native subgrade, lateral spreading, and basal instability (Figure 1).

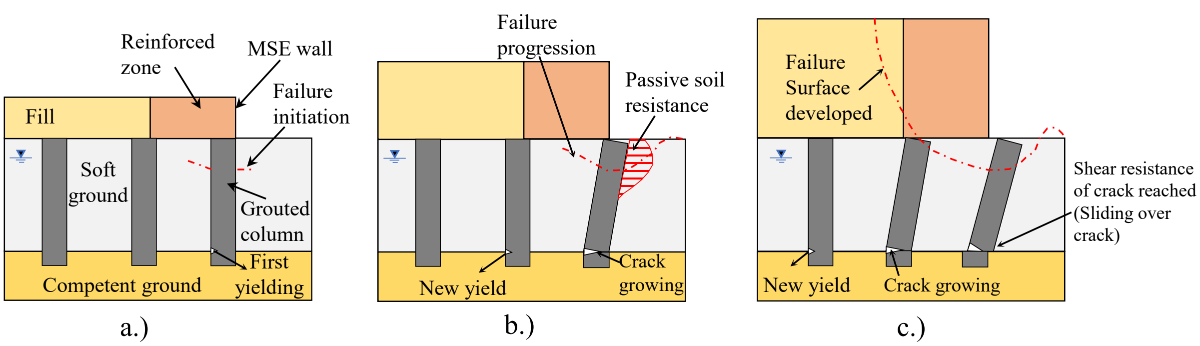



Figure 1: Progressive failure of column-supported system

*Provide context as to how these activities are helping achieve the overarching goal(s) of the project…*

**Defining Failure**:

We will not define "failure" based solely on yielding of the column due to lateral loading (i.e. initial crack formation due to excessive tensile stresses and bending which occur at relatively small lateral deformations). Instead failure and limiting conditions will be based on excessive lateral and vertical deformations that compromise the system's serviceability for intended applications or a threshold limit, beyond which basal instabilities have been reported. Figure 2 shows reported deformations beneath CSE systems and indicates a tentative threshold criteria envisioned to define failure, similar to Matsuo and Kawamura (1977). The number of cases where basal instabilities have been reported in the literature is limited, and therefore supplemented with cases where embankments were not supported on columns (note that these are recorded deformations prior to failure). Defining failure in this manner allows this problem to be studied in a continuum numerical framework (i.e. finite element analyses). It is currently envisioned that a “failure” envelope may be defined based on a threshold limit for deformations (e.g. similar to that shown in Figure 2). Table 1 summarizes the reported case studies for column-supported systems shown in Figure 2.

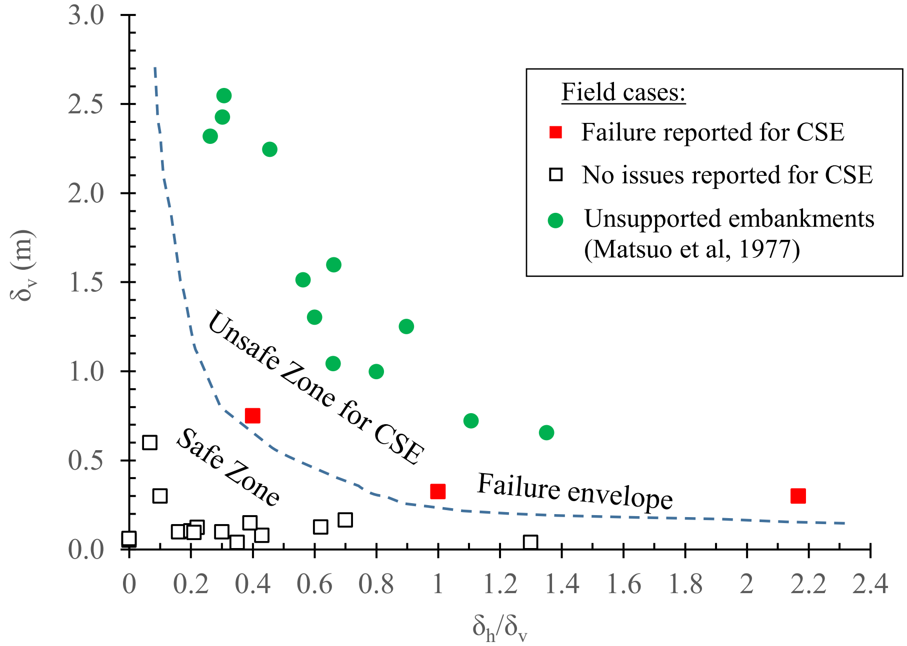



Figure 2: Tentative criteria to define basal instability based on observed deformations beneath column-supported systems. Also shown are reported deformations for cases where basal instabilities were reported beneath unsupported embankments (no CSE).

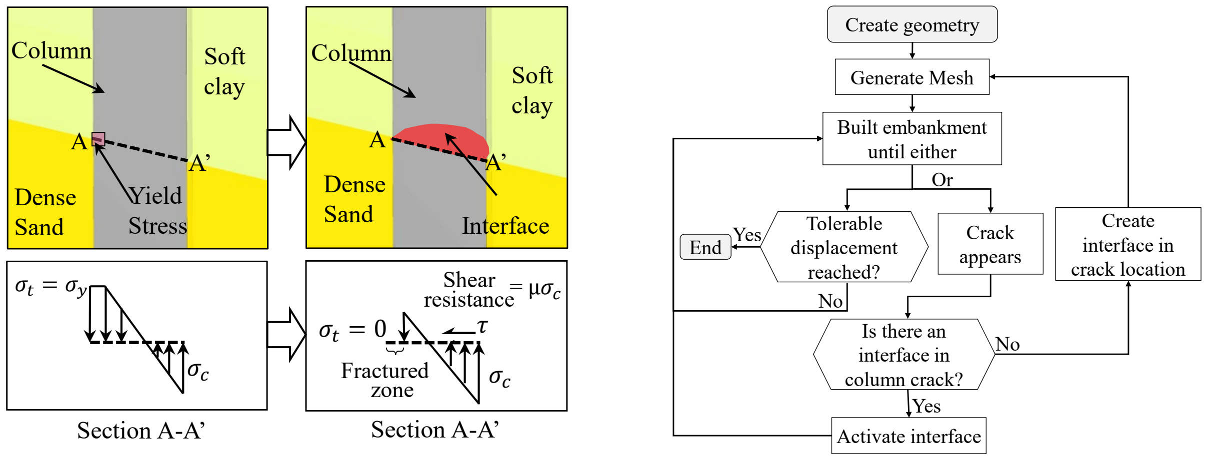
Table 1. Field cases scenarios of column supported embankments

| | Reference | CSE geometry | | | | Column | | Fill | | Subsoil | | | Displacements | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CT | d (m) | s (m) | s'/d | fc' (MPa) | E (GPa) | H (m) | Slope (H:V) | Z (m) | Su (kPa) | $L_{emb}/Z$ | $\delta_v$ (mm) | $\delta_h$ (mm) | $\delta_h/\delta_v$ |
| 1 | Briacon & Simon (2012) | DDC | 0.5 | 2 | 2.3 | 36 | 20 | 5.0 | 1.5:1 | 6-8 | 13 | 0.29 | 100 | 16 | 0.16 |
| | | | 0.5 | 2 | 2.3 | 36 | 20 | 5.0 | 1.5:1 | 10 | 13 | -0.05 | 300 | 30 | 0.1 |
| 2 | Liu et al (2007) | PCHO | 1 | 3 | 1.6 | 15 | 18.2 | 5.6 | 1.5:1 | 10.2 | 10-20 | 0.57 | 104 | 20.8 | 0.2 |
| 3 | Zheng et al (2011) | CFG | 0.4 | 1.5 | 2.2 | 20 | 24.87 | 10.3 | RW | 10.1 | 25 | 1.66 | 52.4 | 0 | 0 |
| | | | 0.4 | 1.5 | 2.2 | 20 | 24.87 | 10.3 | RW | 8 | 25 | 2.36 | 62.3 | 0 | 0 |
| 4 | Zhang et al (2014) | CFG | 0.5 | 2 | 2.3 | 20 | 24.87 | 12.2 | 1.5:1 | 12 | 15-50 | -0.33 | 125 | 27.5 | 0.22 |
| | | | 0.5 | 2 | 2.3 | 20 | 24.87 | 12.7 | 1.5:1 | 14 | 15-50 | -0.14 | 100 | 30 | 0.3 |
| | | | 0.5 | 1.8 | 2.0 | 20 | 24.87 | 11.9 | 1.5:1 | 17 | 15-50 | -0.65 | 127 | 78.74 | 0.62 |
| | | | 0.5 | 1.8 | 2.0 | 20 | 24.87 | 10.0 | 1.5:1 | 23 | 15-50 | -0.74 | 95 | 19.95 | 0.21 |
| 5 | Chai et al (2015) | DCM | 1.2 | 1.9 | 0.6 | 1 | 0.1 | 6.5 | 1.8:1 | 9.5 | 10-20 | -0.11 | 600 | 40.2 | 0.067 |
| 6 | Jamsawang et al (2016) | DCM | 0.6 | 1.5 | 1.3 | 0.94 | 0.092 | 1.5 | 2:01 | 14 | 10-20 | 0.00 | 80 | 34.4 | 0.43 |
| | | | 0.6 | 1.5 | 1.3 | 0.94 | 0.092 | 1.5 | 3:01 | 14 | 10-21 | 0.00 | 40 | 14 | 0.35 |
| 7 | King et al (2017) | DDC | 0.45 | 2.5 | 3.4 | NI | NI | 6.0 | GW & 2.66:1 | 9 | 20-50 | 0.44 | 40 | 50 | 1.3 |
| 8 | Wu et al (2019) | PHCO | 0.4 | 2 | 3.0 | 40.7 | 30 | 40.0 | 1.5-2:1 | 5 to 7 | 19-32 | 1.50 | 165 | 160 | 0.7 |
| | Failure case histories | | | | | | | | | | | | | | |
| 9 | Chai et al (2019) | DCM | 1.2 | 1.93 | 0.6 | 0.6-2.5 | 0.06 | 7.4 | 0.3:1, 1.8:1 | 10.3 | 15-40 | 0.26 | 750 | 300 | 0.40 |
| | | | 1.2 | 1.93 | 0.6 | 0.6-2.6 | 0.06 | 8.4 | 0.3:1, 1.8:2 | 10.3 | 15-41 | 0.36 | 300 | 650 | 2.17 |
| 10 | Wang and Zhang (2019) | PHC | 0.4 | 2.5 | 3.9 | 65.4 | 38 | 7.5 | 1.5:1 | 20 | 7-35 | -0.25 | 325 | 325 | 1.00 |
| | | | 0.4 | 2.5 | 3.9 | 65.4 | 38 | 7.5 | 1.5:1 | 20 | 7-35 | 0.15 | 150 | 58.6 | 0.39 |

Note: CT=Column type; DCM=Deep cement mixing;CFG=Cement-fly ash-gravel; CIP-O=Cast in place-Annulus; DDC: Drilled Displacement columns; PHC=Pre-fabricated high-strength concrete (in Wang Pretensioned high strength concrete; NI=No information; GW: Gabion Wall

**Modeling**:

Challenges associated with modeling the progression of failure and basal instability beneath fill supported on unreinforced rigid elements is simulating formation of cracks and loss of bending stiffness in the column as the fracture propagates. Two approaches to simulate crack formation (i.e. tensile yielding) in grouted columns have been considered: i.) the "discrete-crack" method or ii.) the "smeared crack" approach. The discrete-crack method introduces an interface with a ultimate tensile resistance that allows separation at the crack location as the fracture propagates through the column. Shear resistance at the interface is governed by Coulomb friction (see **Error! Reference source not found.**a. When lateral loading overcomes passive resistance provided by the soil and interface friction (shear resistance) along the crack the column will begin to slide at the fracture location. **Error! Reference source not found.**b shows the numerical procedure adopted to model discrete cracks. One disadvantage is that remeshing the geometry needs to be done whenever a crack appears, and the interface is not predefined. We are currently working to overcome this limitation.




a.) b.)

Figure 3. Numerical methodology to model the fracture process. a.) Stresses in the column before and after the fracture in the column; b.) Flow chart of the numerical procedure.

The smeared crack approach–simulation of strength and stiffness degradation through the zone of fracture via adoption of an appropriate constitutive model—is highly mesh-dependent and issues with numerical convergence often arise. One of the main advantages of using the smeared crack approach is that the energy release rate can be specified to account for the dissipation of energy due to fracture grown and microcracking. However, simulating the dissipation of fracture energy and microcracking is not believed to be a crucial requirement to understand the global behavior of the system as failure progresses.

**Model Calibration**:

Finite element procedures (using PLAXIS 3D) are being calibrated with field monitoring data from our case study at the Council Bluffs Interchange System (CBIS). Soil constitutive parameters and layering have been developed from laboratory test data, borings, and cone penetration tests. Computed results from simulated construction, including vertical and lateral deformations and pore water pressures, will be compared with field instrumentation (settlement plates, multi-point borehole extensometers, inclinometers, and piezometers). As part of model calibration and will examine the computed response (e.g. deformations) and predicted yielding of the columns.

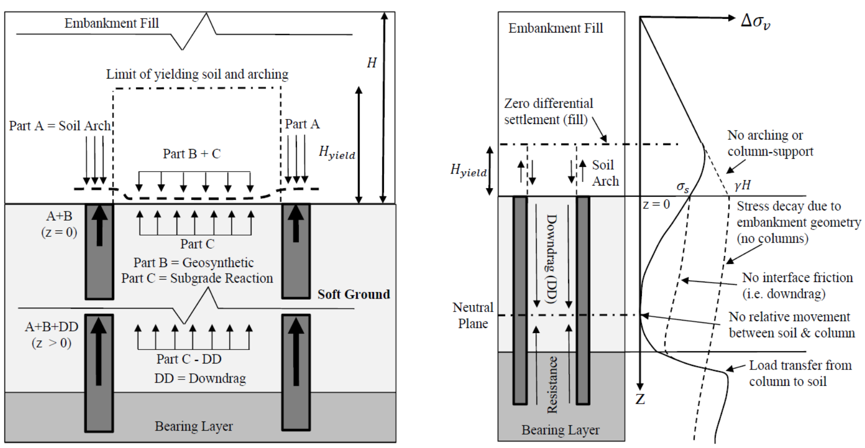
**Parametric Study**:

A parametric study will follow the calibration effort. Table 2 summarizes the conditions that will be tested during the parametric study. Their hypothesized influence is based largely on the finding reported in an initial evaluation of the subgrade response at the CBIS project site (Gallant et al. 2019). An important demonstration from this initial effort was that stresses imparted in the native subgrade are significantly influenced by hang-up effects due to soil-column interface friction and downdrag, which limit the depth of "appreciable stressing" between columns (see Figure 4). From that perspective, downdrag is beneficial with regards to reducing stress applied to the native subgrade at depth. Additionally, it's envisioned that the strength and stiffness of a shallow crust layer with be influential in the vertical and lateral deformations observed beneath sloping fill or an MSE wall (i.e. where unbalanced loads exist). A stiff crust may effectively perform as a shallow beam or slab and offer lateral support—an important consideration with regards to hypothesized progression of failure discussed earlier (i.e. the lateral loading must overcome passive resistance provided by the soil to result in sufficient movement and inability to transfer load to more competent ground).

**Table 2**. Variables to analyze in the parametric study and their importance

| Variable | Hypothesized Influence | Importance |
| --- | --- | --- |

| | | | |
|---|---|---|---|
| s'/d | Clear spacing ratio | Greater s'/d increases stresses in soil and lateral forces on columns. | *** |
| $Z_s$ | Clay thickness | Columns will yield earlier (lower fill height) with decreasing $Z_s$ due to increased curvature in the column. However, due to interface friction the clay thickness may be limited in its effect on vertical deformations and stressing of soil at depth. | * |
| $s_u$ | Shear strength of soft clay | Greater $s_u$, increases passive resistance, thus increases the resistance to the column to deformations (both before and after fracturing occurs). | *** |
| $f_s$ & $H_1$ | Interface friction and a crust thickness | Increasing interface stiffness and thickness of stiff crust ($H_1$) the stresses in subsoil (Gallant et al, 2019). Higher compression forces in the column, reduces the tensile stresses, thus increasing global stability. | ** |
| Load type | Unbalanced loads configuration | MSE load will produce greater lateral loads than slope type, thus basal instability is expected first in the MSE wall configuration | ** |




(a) (b)

Figure 4. a.) Load distribution within a unit cell; b.) Generalized vertical effective stress through the fill and subgrade at the center of a unit cell (Gallant et al, 2019).

*Describe any accomplishments achieved under the project goals…*

An article evaluating the subgrade response for the CBIS project site was accepted for publication in a peer-reviewed journal.

*Complete the following tables to document the work toward each task and budget (add rows/remove rows as needed)…*

| Table 1: Task Progress | | | |
|---|---|---|---|
| **Task Number** | **Start Date** | **End Date** | **Percent Complete** |
| Task 1: Understand the stresses in subsoil | 06/2018 | 06/2019 | 100% |
| Task 2: Establish a numerical approach to assess the cracking and fracture process | 06/2019 | 09/2019 | 100% |
| Task 3: Calibrate of Case Study with lateral and vertical deformations | 06/2019 | 01/2020 | 50% |
| Task 4: Perform parametric study | 01/2020 | 04/2020 | 5% |
| Task 5: Create a design guideline | 03/2020 | 05/2020 | 5% |

| Table 2: Budget Progress | | |
|---|---|---|
| **Entire Project Budget** | **Spend Amount** | **Spend Percentage to Date** |
| $33,380 | $15,050 | 45.1% (12/31/2019) |

*Describe any opportunities for training/professional development that have been provided…*

*Describe any activities involving the dissemination of research results (be sure to include outputs, outcomes, and the ways in which the outcomes/outputs have had an impact during the reporting period. Please use the tables below for any Publications and Presentations in addition to the description of any other technology transfer efforts that took place during the reporting period. )… Use the tables below to complete information about conferences, workshops, publications, etc**. List all other outputs, outcomes, and impacts after the tables** (i.e. patent applications, technologies, techniques, licenses issued, and/or website addresses used to disseminate research findings).*

| Table 3: Presentations at Conferences, Workshops, Seminars, and Other Events | | | | |
|---|---|---|---|---|
| **Title** | **Event** | **Type** | **Location** | **Date(s)** |
| N/A | | | | |

| Table 4: Publications and Submitted Papers and Reports | | | | |
|---|---|---|---|---|
| **Type** | **Title** | **Citation** | **Date** | **Status** |
| Journal Case study | 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 (Accepted). | 2019 | Accepted |

**Participants and Collaborators:**

*Use the table below to list all individuals who have worked on the project.*

| Table 5: Active Principal Investigators, faculty, administrators, and Management Team Members | | | |
|---|---|---|---|
| **Individual Name** | **Email Address** | **Department** | **Role in Research** |
| Dr. Aaron Gallant | | | |
| | | | |

*Use the table below to list all students who have participated in the project.*

| Table 6: Student Participants during the reporting period | | | | |
|---|---|---|---|---|
| **Student Name** | **Email Address** | **Class** | **Major** | **Role in research** |
| Danilo Botero-Lopez | | Master | Master of Civil Engineering | ? |

*Use the table below to list any students who worked on this project and graduated during this reporting period.*

| Table 7: Student Graduates | | | |
|---|---|---|---|
| **Student Name** | **Role in Research** | **Degree** | **Graduation Date** |
| N/A | | | |

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

| Table 8: Research Project Collaborators during the reporting period | | | | | | |
|---|---|---|---|---|---|---|
| **Organization** | **Location** | **Contribution to the Project** | | | | |
| | | **Financial Support** | **In-Kind Support** | **Facilities** | **Collaborative Research** | **Personnel Exchanges** |
| University of Maine | Orono, Maine | | x | | | |
| Deep Foundations Institute (DFI) | | | x | | | |

*List all other outputs, outcomes, and impacts here (i.e. patent applications, technologies, techniques, licenses issued, and/or website addresses used to disseminate research findings). Please be sure to provide detailed information about each item as with the tables above.*

*Have other collaborators or contacts been involved? If so, who and how? (This would include collaborations with others within the lead or partner universities; especially interdepartmental or interdisciplinary collaborations.*

**Changes:**

*Discuss any actual or anticipated problems or delays and actions or plans to resolve them…*

*Discuss any changes in approach and the reasons for the change…*

**Planned Activities:**

The future work will be focused on calibrate the case study with the field case study with the instrumentation, laboratory data, and field tests information. Then, a parametric study will be performed to understand the behavior of the systems under different conditions.

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