Alternatively, the efficacy of load transfer may be evaluated based on settlement (e.g. Nunez et al., 2013):

$$E_\delta = 1 - \frac{\delta}{\delta_{NC}} \quad (2)$$

where δ is settlement of native ground *with* columns and δ_{NC} is the estimated settlement *without* column support. This metric is more useful for serviceability considerations, but inherently dependent, in part, on E_σ, as well as compressibility/stiffness of the underlying native ground.

Pile caps, though less common today, increase the area replacement ratio of a unit cell and efficacy of load transfer. Alternatively, geosynthetic reinforcement may be embedded in the lower fill to construct a load transfer platform (LTP) and help "bridge" loads between columns (Figure 1a) . Geosynthetic reinforced column-support (GRCS) and application of an LTP has gained wider acceptance and use in lieu of pile caps; it reduces applied load and settlement in native ground with greater column spacing and a smaller area replacement ratio (Han and Gabr, 2002, Liu et al., 2007; Huang et al., 2009; Briancon and Simon, 2012; Rowe and Liu, 2015). Regardless of the mechanisms contributing to load transfer *above* the columns, a portion of the embankment load is applied to native ground and has been the subject of extensive research (e.g. Guido et al., 1987; Hewlett and Randolph, 1988; Low et al., 1994; Russell and Pierpoint, 1997; Filz and Smith, 2007; Hong et al., 2007; Sloan et al., 2011a; van Eekelen et al., 2013; Zhuang et al., 2013; van Eekelen et al., 2015; Zhuang and Ellis, 2016). However, these loads are further influenced via soil-structure interaction at depth, and undoubtedly contribute to the performance of CSE's.

If soil does not interact with columns (i.e. "smooth" column), the reduction in applied stress at depth is due solely to arching and bridging of embankment loads by the LTP (Figure 1b). Settlement of native soil relative to the columns (i.e. downdrag) results in "hang up" effects that create a subsurface arching mechanism, increasing column loads and reducing applied stress in native ground (Figure 1b). The dissipation of load in soft ground *below* the embankment is dependent on the soil-column interface shear strength, stiffness, and relative deformation of the soil and columns (Chen et al., 2008; Nunez et al., 2013; Liu et al., 2017). Soil-column interaction likely plays an important role in performance of GRCS systems and their efficacy in settlement reduction. Though previous numerical, field, and laboratory studies have considered the compressibility of native ground when evaluating load transfer, more focus has been given to the influence of subsoil support and geosynthetics on differential settlement within the embankment fill itself. Less attention and limited field data has been made available to evaluate load transfer and settlement at depth, which inherently affects total settlement, H_{cr}, and tensile stresses in the geosynthetic. Load transfer and settlement at depth may also an important consideration if columns are protecting buried structures, existing utilities, culverts, etc.

This case study examines the performance of GRCS during filling of MSE walls and embankments constructed over a layer of compressible clay, and focuses on subsurface deformations, efficacy of settlement reduction, and inferred stress changes at depth. Computed results from a quasi-3D finite element analysis of a unit cell are compared with field data and inferred stress changes to investigate the influence of soil-column interaction on performance.

SITE DETAILS

GRCS was chosen to facilitate embankment and MSE wall construction for bridge abutments and approach embankments near an existing levee system as part of upgrades and improvements to the Council Bluffs Interchange System (CBIS), located outside Omaha, Nebraska in Council Bluffs, IA. Improvements included lane expansion and elevation of interstate I-29 above flood levels near Mosquito Creek. Filling of approach embankments and bridge abutments on the north and south sides of the new bridge (Figure 2) required changes in grade as great as 11m. MSE walls were constructed adjacent to existing I-29 traffic lanes to limit the footprint of required fill and to allow traffic continued access to the roadway throughout construction. Unreinforced concrete rigid inclusions were used as support columns and installed with a drilled displacement tool. GRCS was chosen to (i) limit settlement of approach embankments and abutments, (ii) permit rapid filling and erection of a new bridge crossing the levee system, and (iii) to limit deformations and maintain stability beneath the existing highway during construction.

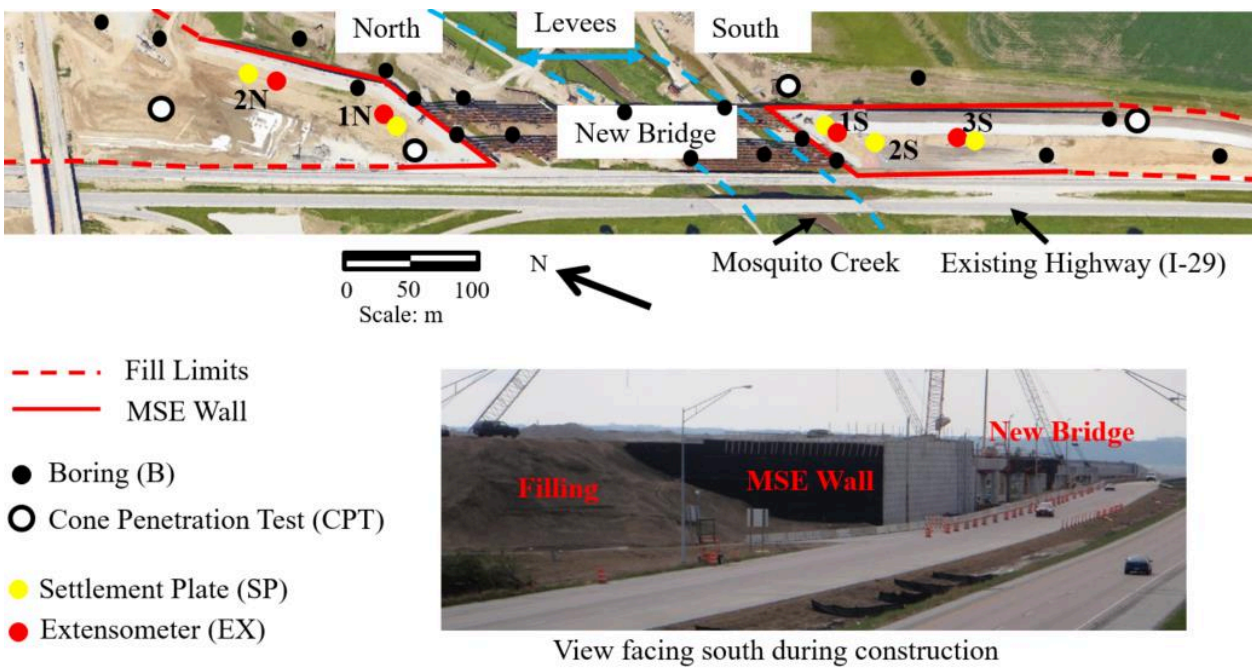


Figure 2: Site details and fill/column limits for bridge construction

Five instrumentation locations on the north and south ends of the site (1N, 2N, 1S, 2S, 3S) are shown in Figure 2 and were used to monitor surface and subsurface deformations during filling (with settlement plates and multi-point extensometers). Columns were placed in a square grid arrangement with a diameter and spacing of 0.46m and 1.83m, respectively. Four layers of geotextile were used to reinforce the overlying fill and construct the LTP. Details regarding local placement of instrumentation, geotextile reinforcement, and column dimensions are summarized in Figure 3. All instrumentation was placed at the center of the square-grid arrangement to capture the maximum deformations between columns. Settlement plates were located at the interface of native ground and the LTP and extensometers extended from the original ground surface to depths of interest. Settlement plates and extensometers were not placed in the same unit cell and located adjacent to one another.

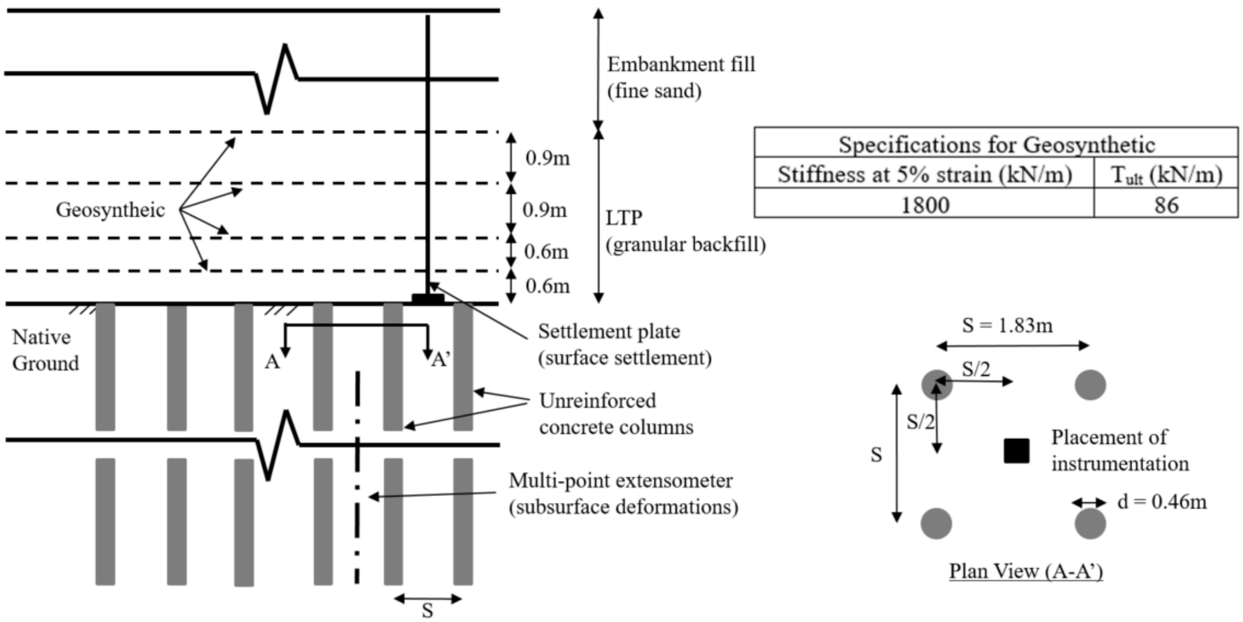


Figure 3: Arrangement of columns, LTP/geosynthetic, and instrumentation

SUBSURFACE CONDITIONS

Cone penetration tests (CPT) and soil data collected from borings (Figure 4) indicate subsurface conditions generally consist of a compressible, heavily overconsolidated to normally consolidated clay, underlain by loose silty sand, medium dense to dense sand, and bedrock. Column support was designed to transfer fill loads through the clay into the underlying granular material. The thickness of clay and loose sand varied on the north and south sides of the levee system, but soil layers generally exhibit the same strength and stiffness characteristics, stress history, and layering. Based on CPT soundings, borings, and column installation logs, the clay varies in thickness from approximately 4.5 to 11m across the site and the looser layer of silty sand extends to depths ranging from 8 to 12m. Bedrock depths ranged from 26-29m. Figure 4 shows the interpreted overconsolidation ratio (OCR) from CPT correlations (Robertson, 2009) and results from 1-D compression tests. Also shown is the interpreted undrained shear strength (S_u) from CPT correlations and laboratory measurements from UU TXC tests.

A local correlation developed with results of 1-D compression tests and natural water contents, ω, was used to estimate compressibility of the clay during this study. The correlated virgin compression and recompression indices, C_c and C_r, are applicable to the water content profile shown in Figure 4:

$$C_c = 0.71\omega + 0.0834 \tag{3}$$

$$C_r = 0.09\omega - 0.019 \tag{4}$$

Void ratios in the clay, e_o, were estimated based on natural water contents, assuming a specific gravity of 2.65. Maximum past-pressures, used to estimate settlement efficacy and infer stress changes in the clay (discussed later), are based on the interpreted OCR profile shown in Figure 4. Laboratory tests were not performed on samples obtained at shallower depths within the clay, and thus assumed to have a maximum OCR of 10. In situ lateral earth pressures and K_o (applicable to finite element analyses presented later) were evaluated using the well-known relationship developed by Mayne and Kulhawy (1982) for overconsolidated soils, assuming an effective friction angle of 26 degrees. Basic soil parameters for each layer are summarized in Table 1 and the estimated thickness of the clay, loose sand, and fill heights for each instrumented location are summarized in Table 2.

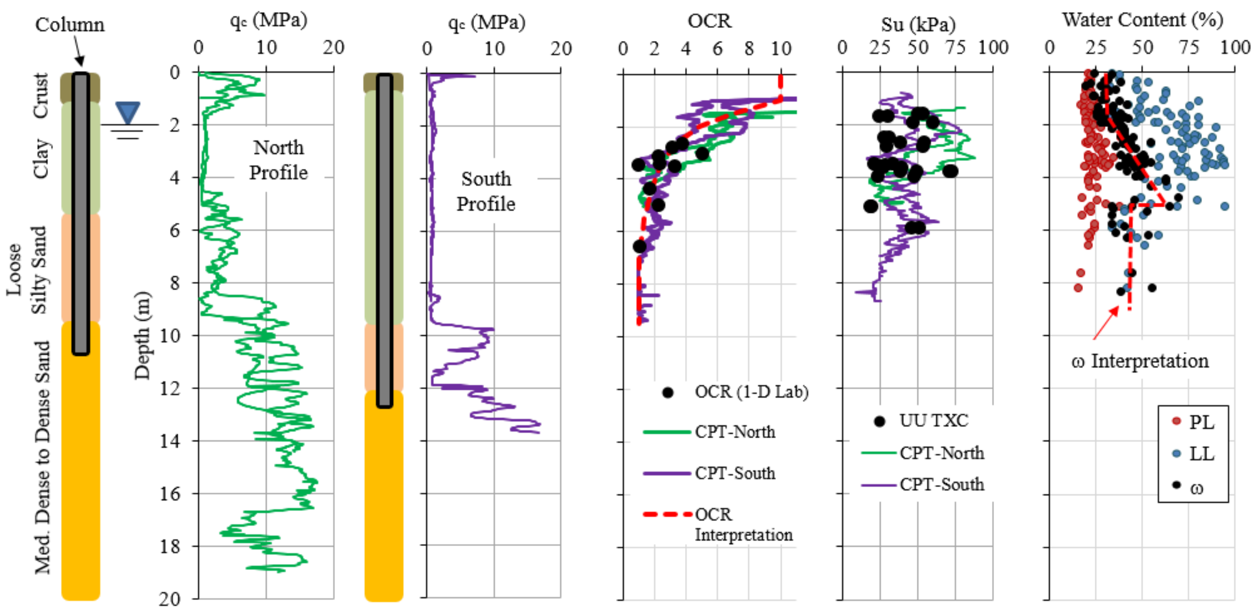


Figure 4: Subsurface conditions

Table 1: Basic soil parameters

Layer	Clay	Loose Sand	Dense Sand	Fill
ϕ' (°)	26	30	35	33
c' (kPa)	-	-	-	-
S_u (kPa)	25-75	-	-	-
C_c	0.30-0.47	-	-	-
C_r	0.046-0.069	-	-	-
e_o	0.80-1.46	-	-	-
E (MPa)	-	15	40	30
ν	-	0.15	0.15	0.15
K_o	0.56-1.54	0.50	0.43	0.5
γ (kN/m^3)	18	19	20	20

Table 2: Estimated layer depths and column spacing for instrumented locations

Layer Thickness (m)	Clay	Loose Sand	Fill Height	Instrumentation
1N (s = 1.83m)	4.6	8.5	11.0	SP, MPE
2N (s = 1.83m)	4.6	8.5	9.1	SP, MPE
1S (s = 1.83m)	9	12	8.8	SP, MPE
2S (s = 1.83m)	9	12	8.0	SP
3S (s = 1.83m)	9	12	6.9	SP, MPE
SP: Settlement plate				
MPE: Multi-point extensometer				

OBSERVED SURFACE AND SUBSURFACE DEFORMATIONS AND INFERRED STRESS CHANGES AT DEPTH

Observed deformations and inferred stress changes in native ground beneath the column-supported fill are presented herein. Figure 6 shows a comparison of measured subsurface deformations with estimated 1-D settlements *in the absence of column-support*. For reference, surface settlement measured by settlement plates located adjacent to multi-point extensometers are also shown. This combined observation generally indicates the majority of settlement and strain accumulate at shallower depths within the clay. The comparison in Figure 5 is made to illustrate the efficacy of settlement reduction, and indicates column support effectively transfers the majority of embankment loads through the clay and into the denser underlying material. Settlements were also measured beneath embankments at a nearby location where column support was not employed, and is compared with observed settlements at GRCS locations in Figure 6a. These embankments were also constructed as part of the CBIS project. Subsurface conditions at this nearby location generally consists of the same soil layers and material properties as conditions presented earlier. This comparison is made to (i) further illustrate the efficacy of settlement reduction with GRCS and (ii) validate the methodology and soil parameters chosen to estimate settlement at GRCS location in the absence of column support (i.e. Figure 5).

Good agreement between estimated and observed values for nearby locations where columns were not used suggests predicted settlements (without columns) for the instrumented GRCS locations are reasonable and applicable for evaluation of E_δ (discussed later). Estimates of settlement *without columns* were computed using the interpreted OCR profile shown in Figure 4, consolidation and stiffness parameters presented in Table 1, and layer thicknesses shown in Table 2. To account for embankment geometry, changes in vertical stress were estimated using Boussinesq elastic solutions (e.g. Fadum, 1948; Osterberg, 1957; U.S. Navy, 1986), though no less than 70% of the full weight of the embankment weight was computed in the clay at any location. It was assumed that compression at depths greater than 15m does not appreciably influence total settlement, which appears reasonable based on measured subsurface deformations (Figure 5).

Despite a wide range of estimated settlement in the *absence* of column support, due to fill heights that ranged from 6.9m to 11m and clay thickness (H_c) that varies from 4.6m to 9m, a narrow range of settlement was observed for fill locations with columns (Figures 6a). Though settlements generally increase with fill height (Figure 6b), more strain and settlement accumulate at shallower depths in the clay (Figure 5). This observation suggests soil-column interaction may limit the "depth of influence" that embankment loads (i.e. σ_s in Figure 1b) have in soft native ground, limiting the contribution that clay thickness has on settlement beneath CSE's.

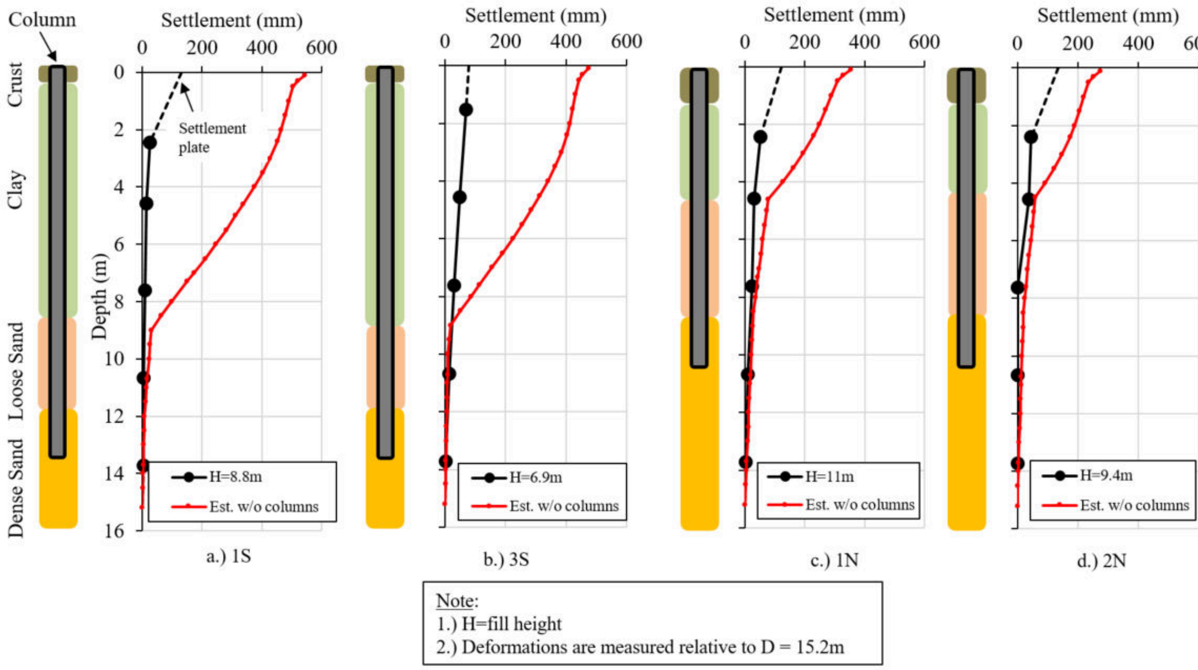


Figure 5: Comparison of observed subsurface deformations with GRCS and estimated deformations *without* implementation of GRCS

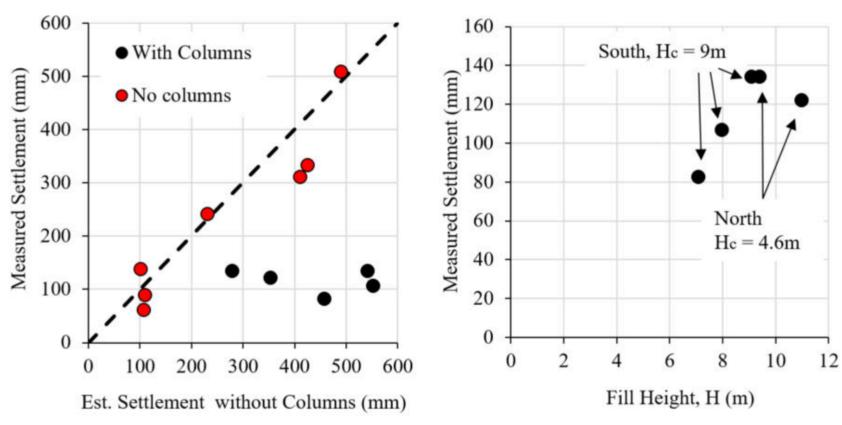


Figure 6: a.) Settlement with and without columns; b.) Settlement vs. fill height

Stress changes in the clay were inferred at depth by evaluating changes in vertical stress required to induce an equivalent amount of *observed compression between anchorage points*. This simplified methodology used the compressibility and interpreted stress-history in the clay (Figure 4) and assumed 1-D compression at the center of a unit cell. Analyses indicate *changes* in vertical effective stress and SRR decrease with depth (Figure 7), supporting the hypothesis that soil-structure interaction limits the depth of influence that embankment loads have in the clay. Inferred stress changes at southern locations (greater clay thickness) indicate the efficacy of stress reduction (E_σ in eq. 1) increases to 0.8 and 0.95 at depths greater than 4.5m. The hang up effects and *subsurface arching* mechanism implied by inferred stress changes suggests columns carry 80 to 95% of embankment load at depth via (i) arching and load transfer at the head of the column *and* (ii) soil-column interaction and downdrag from the clay. An extrapolation of SRR and E_σ to the original ground surface is shown to suggest possible stress reduction due to arching and load transfer at the head of the column, but is *not* based on inferred stress changes from measured deformations. The limiting influence of embankment load at depth results in an appreciable increase in the efficacy of settlement reduction (E_δ from eq. 2) with clay thickness, as shown in Figure 8.

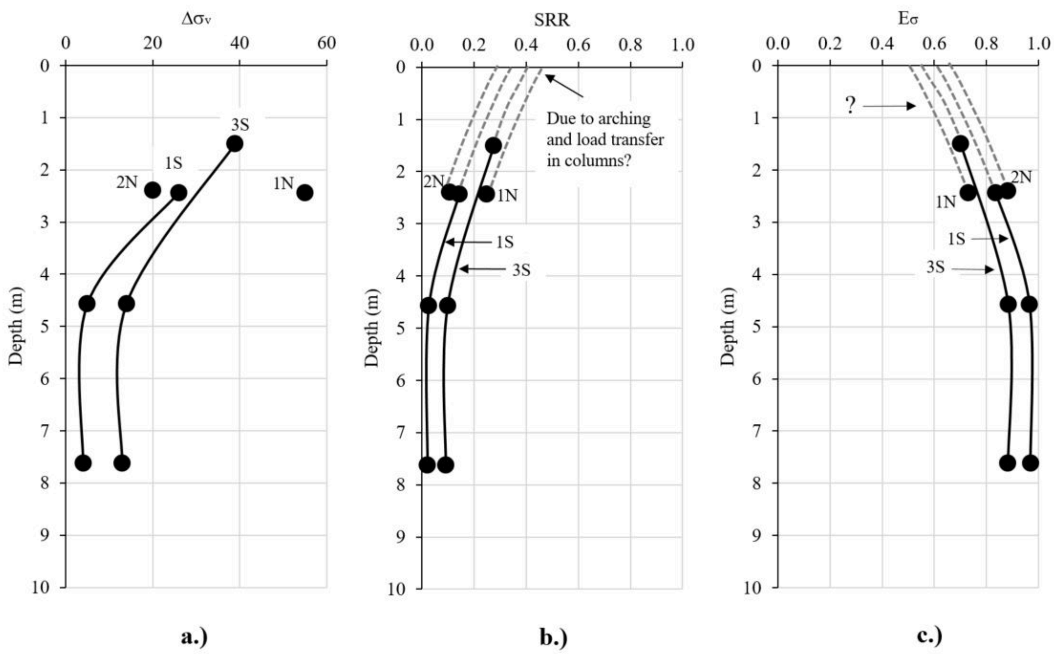


Figure 7: a.) Inferred changes in vertical effective stress in clay from subsurface deformations; b.) inferred SRR; c.) inferred stress efficacy

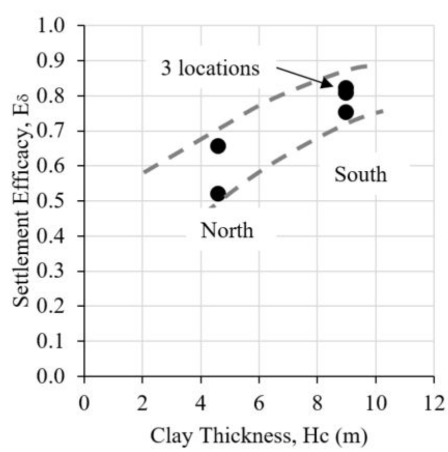


Figure 8: Settlement efficacy vs. clay thickness

EVALUATING INFLUENCE OF CLAY-COLUMN INTERACTION ON SETTLEMENT AND LOAD TRANSFER IN NATIVE GROUND

To further evaluate the relative contribution soil-column interaction plays on settlement reduction, a quasi-3D finite element analysis (FEA) was performed to evaluate filling of a unit cell (quarter cell is modeled due to symmetry of column arrangement) for the northern and southern soil profiles (Table 2). The commercial finite element code Plaxis 3D, version 2016.01 was used for the analyses. The finite element mesh, layering, and assumed OCR profile for the clay are presented in Figure 9 and constitutive soil parameters for each layer are given in Table 3. Behavior of the fill and clay were modeled using the elasto-plastic Hardening Soil (HS) model with stress dependent stiffness. HS stiffness parameters for the clay were calibrated from 1-D consolidation data and it was assumed that column installation does not appreciably influence compressibility and stiffness of native ground. Behavior of the dense and loose sand were simulated with the elastic-perfectly plastic Mohr-Coulomb (MC) model. Linear elastic behavior was assumed for the concrete column. Geosynthetics were simulated as linear elastic tensile elements with the strength and stiffness specified for the CBIS project (Figure 3).

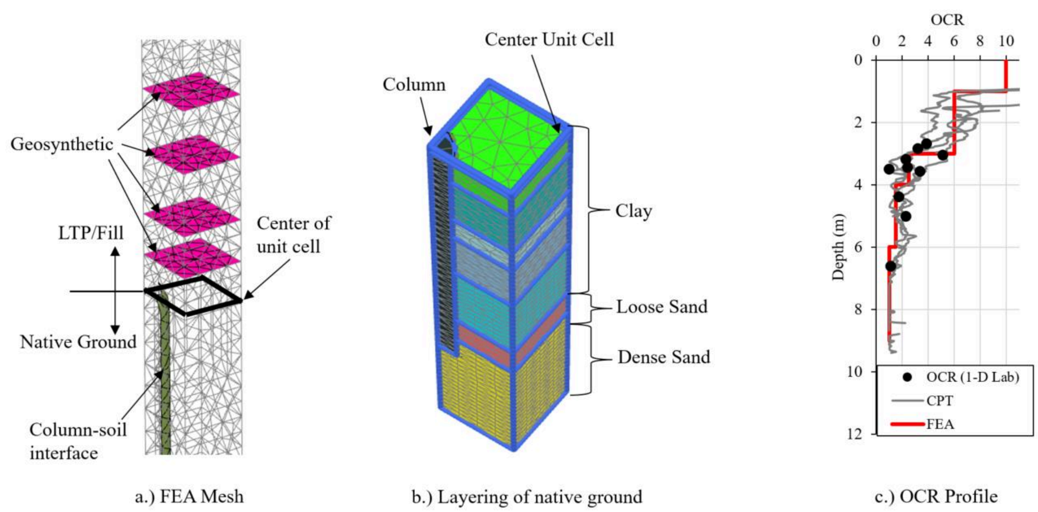


Figure 9: a.) FEA mesh; b.) FEA Layering; c.) OCR used for FEA

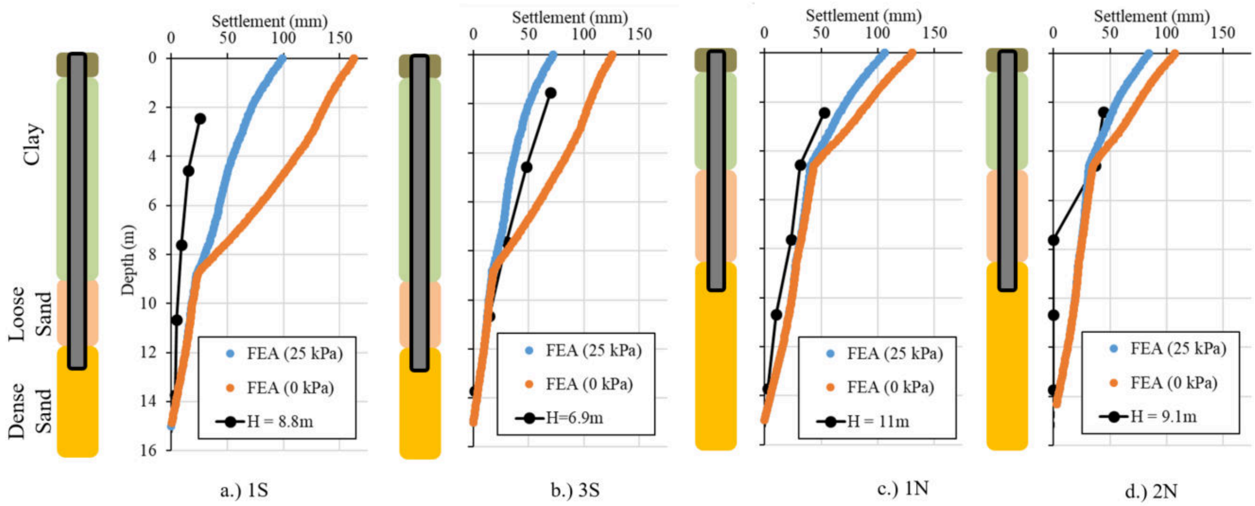
The purpose of this numerical study was to investigate the influence of *clay*-column interface shear strength and clay thickness on settlement, load transfer at depth, and settlement efficacy. Interface shear strength in the clay was a manual input (25 kPa) and based on an evaluation of unit side resistance with the LCPC method (Bustamante and Gianeselli, 1982) and site-specific CPT data. Correlations for displacement foundations were used during the evaluation of side resistance (a drilled displacement tool was used for column installation). The assumed value of 25 kPa also appears reasonable based on measured undrained shear strength in the clay (Figure 4). A separate analysis neglected interface shear strength in the clay (i.e. smooth column) to evaluate the influence of clay-column interaction on performance and load transfer at depth. Simulated filling did not consider excess pore pressure generation and dissipation, as clay-column interface shear strength was a manual input and not a computed constitutive response.

Table 3: Constitutive Material Parameters

	Parameters	Fill/ LTP	Clay (0-1m)	Clay (1-3m)	Clay (3-4m)	Clay (4-6m)	Clay (> 6m)	Loose Sand	Dense Sand	Column
HS	E_{50}^{ref} (MPa)	30	1.3	1.3	1.3	1.3	1.3	-	-	-
	E_{oed}^{ref} (MPa)	30	1.3	1.3	1.3	1.3	1.3	-	-	-
	E_{ur}^{ref} (MPa)	90	6	6	6	6	6	-	-	-
	m	0.5	0.9	0.9	0.9	0.9	0.9	-	-	-
	ν_{ur}	0.2	0.2	0.2	0.2	0.2	0.2	-	-	-
	K_o^{NC}	0.46	1	1	1	1	1	-	-	-
	R_f	0.9	0.9	0.9	0.9	0.9	0.9	-	-	-
	P^{ref} (kPa)	100	100	100	100	100	100	-	-	-
MC	E (MPa)	-	-	-	-	-	-	15	40	-
	ν	-	-	-	-	-	-	0.15	0.15	-
LE	E (GPa)	-	-	-	-	-	-	-	-	21.5
	ν	-	-	-	-	-	-	-	-	0.15
State	OCR	1	10	6	2.5	1.5	1	-	-	
	Ko	0.46	1.54	1.23	0.84	0.67	0.56	-	-	
Strength	ϕ' (°)	33	0	0	0	0	0	0	35	
	Su (kPa)	0	30	30	30	30	30	0	0	
	Interface (kPa)	Rigid	25	25	25	25	25	Rigid	Rigid	

Computed and observed subsurface deformations and inferred SRR for each extensometer location are presented in Figures 10 and 11, respectively. Generally, subsurface deformations *and* SRR in the clay show reasonable agreement between field measurements and computed results when clay-column interface shear strength *is considered*. Note that computed results do not represent any effort taken to perform inverse analyses to establish a better fit; and settlement is controlled, to a large extent, by stiffness parameters calibrated from 1-D tests and clay-column interface shear strength. In any case, relatively good agreement between field measurements and computed results suggest the simulation of filling with a unit cell is a reasonable approach to evaluate subsurface behavior and load transfer at depth beneath the column-supported fills.

When clay-column interface shear strength in the clay is neglected, computed SRR shows a slight decrease at the original ground surface (depth = 0) due to increased settlement and arching in the fill. However, at depth the columns no longer absorb load via downdrag and SRR is greater than computed results that consider interface shear strength (Figure 11). This results in increased subsurface deformations and settlement (Figure 10). The influence of the soil-column interface shear strength on total settlement decreases with decreasing clay thickness. For southern locations 1S and 3S (clay thickness = 9m) computed settlement increased 63% and 77% when interface shear strength in the clay was neglected, while settlement increased 24% and 22% for northern locations 1N and 2N (clay thickness = 4.6m). This numerical observation highlights the important role column interface shear strength plays on settlement reduction in native ground, especially as thickness of the compressible layer increases. Because column (material) type plays a large role in interface shear strength, greater settlements may be anticipated for smooth columns (e.g. steel) than rough columns (e.g. concrete), and should be considered in the design of CSE's.



Note:
1.) H=fill height
2.) Field deformations are measured relative to D = 15.2m
3.) FEA (column-soil interface shear strength in clay)

Figure 10: Computed and observed subsurface deformations with varying interface shear strength in clay

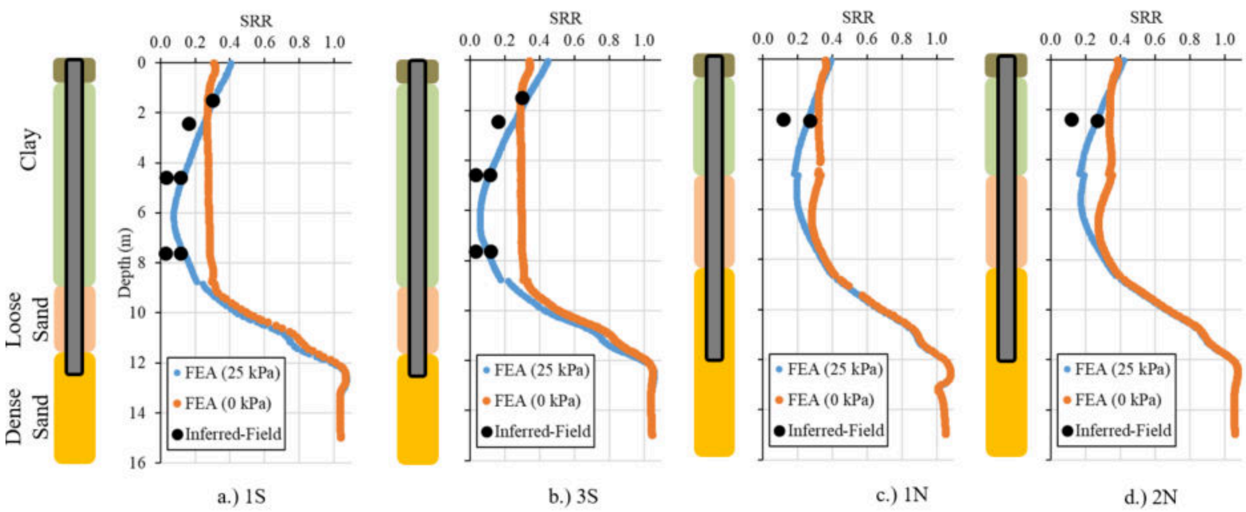


Figure 11: Computed and inferred SRR with varying interface shear strength in clay