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Technical Note:

Incremental Strength Gain Considerations in Staged Roadway Construction

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Abstract: This paper presents an alternative construction method of a highway along coastal area underlain by a thick normally consolidated very soft organic clay, which due to its remote location, mitigations to strengthen the soft clay are deemed too costly and/or require significant time to mobilize. Without mitigations, the presence of this very soft clay necessitates the roadway embankment to be constructed in phases to allow partial consolidation of clayey soils to take place before additional embankment fill can be placed. The stability of partially built embankment is evaluated, and the fill thickness and staging time for each phase are adjusted to meet the stability safety requirements. The settlement due to fill placement can be estimated at each construction phase and included as an overbuilt to the next fill placement thickness. Impacts of soil horizontal and vertical movements due to filling to pile foundations are also be discussed.

Keywords: Soft ground; consolidation; incremental strength gains; staged construction; wick drains; lateral squeeze; down drag.

Introduction

Roadway construction on soft ground (clayey soils) is increasingly common, as the development of infrastructures is rapidly expanding into rural and coastal areas. The major challenges with roadway construction on soft clayey soils are stability of roadway embankment during filling and excessive settlements following placement of roadway embankment fill. Mitigations typically include installation of wick drains and preload to accelerate soil consolidation process, ground improvement to increase soil's strength and stiffness, and/or installation of geogrids to reinforce soils and distribute loads. These mitigation measures, however, could be costly or simply not readily available in remote rural areas.

As part of a highway expansion project, new bridge structures and roadway embankments are to be built south of an existing highway system. Cantilever walls are used to retain the embankment and approach fills. These abutment and wing walls, in turn, are supported using 1,005-mm diameter (D) bored piles, spaced approximately 3D center-to-center. Figure 1 shows the layouts of the bridge and retaining walls. The proposed highway will traverse along a coastal area underlain by a ±10-m thick very soft organic clay deposit at shallow depth.

Construction of the roadway embankment requires placement of up to 5.5-m fill on this very soft clayey soil deposit along the roadway alignment and at bridge abutments. The shear strength of this existing sub-grade clayey soils is too low to allow for a rapid construction of the embankment fill to its full height in one construction stage, while maintaining the recommended minimum factor of safety against slope instability.

Various ground reinforcements and improvements were considered. However, they were deemed too costly and/or required lengthy mobilization time to bring the necessary equipment and materials to the project site. Construction of the embankment, thus, needs to be accomplished in stages, allowing time for partial consolidation and strength gain in the sub-grade soils between stages. This staging of the construction works requires careful evaluations to maintain stability during construction and to prevent embankment overloading. In addition, as the settlements in the soft clay deposit take place during embankment staged construction, the impacts of soil vertical (settlement) and horizontal (lateral squeeze) movements induced by the filling on the bridge and wall pile foundations need to be evaluated to ensure that the piles will not be overstressed.

Subsurface Soil and Groundwater Conditions

The soil investigation comprised of Standard Penetration Test (SPT) soil borings and Cone Penetration Test (CPT) soundings. The data collected from these soil borings and CPT soundings indicates the presence of a very soft organic clay deposit from depths of ±2 to 13 m below existing ground. Figure 2 depicts the cone and sleeve resistances recorded in one of the CPT

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soundings, showing the existence of a thick organic clay with very low strength from depths of ±4 to 13 m. Other CPT soundings and soil borings encountered similar soil conditions along the roadway alignment.

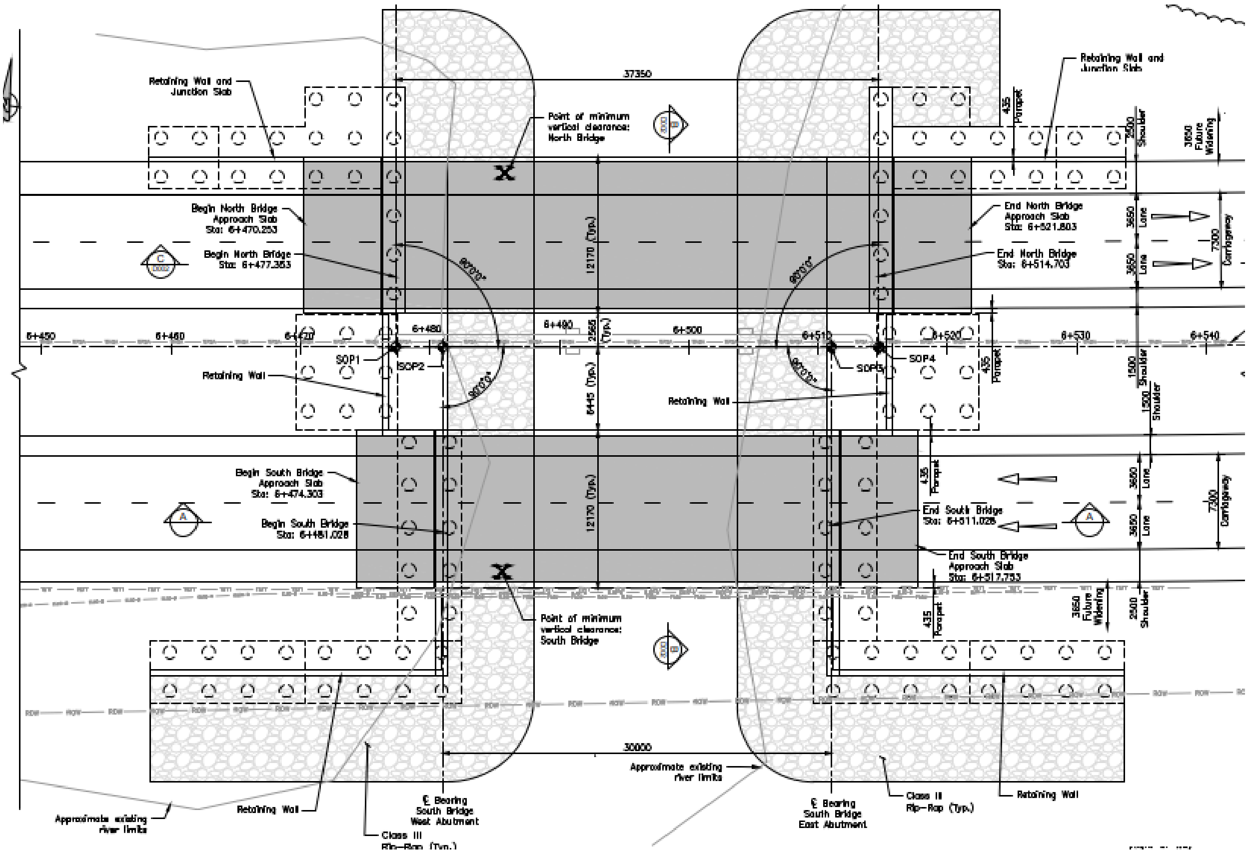


Figure 1. Layouts of Bridge and Retaining Walls

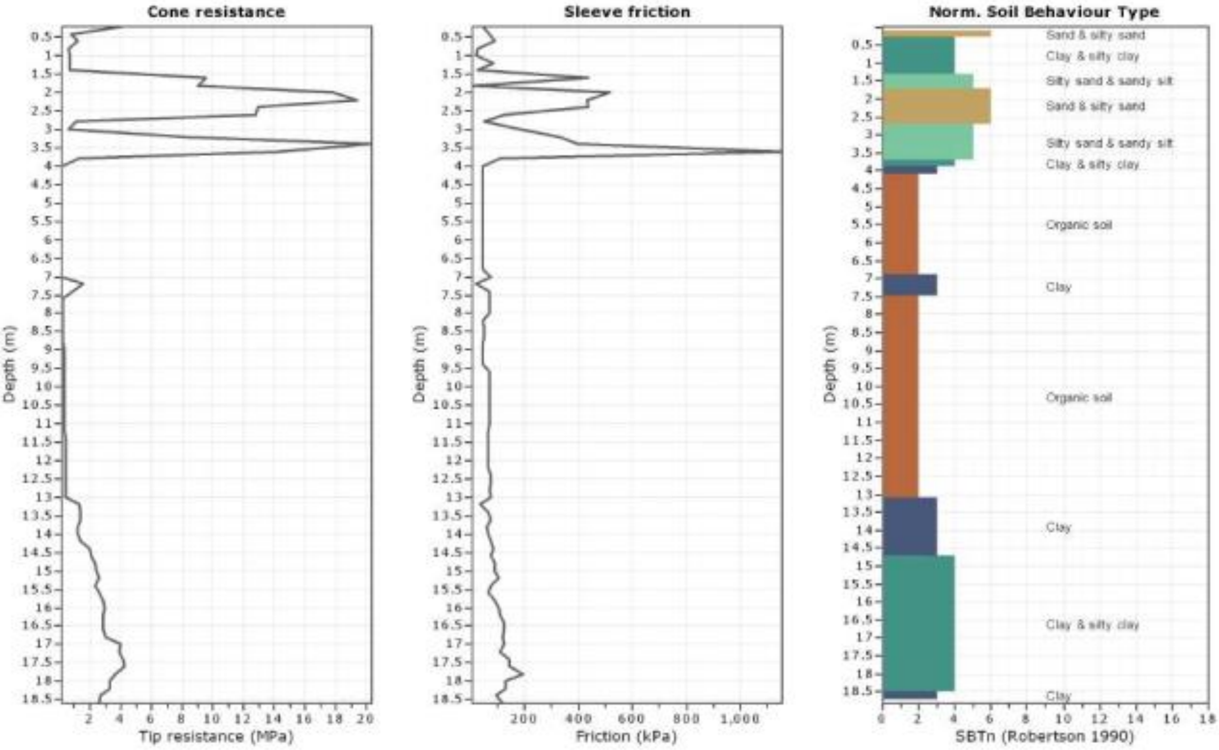


Figure 2. Recorded Cone and Sleeve Resistances and Interpreted Soil Type in One of CPT Soundings

The idealized soil profile for analysis and the geotechnical engineering properties of the various soil units encountered along the roadway are summarized in Table 1. They were developed using the data collected in the soil borings and CPT soundings, as well as the results of field and laboratory tests. Specifically, the undrained shear strength (S_u) of soft clay was estimated from correlation with CPT tip resistances, and the coefficient of consolidation (C_v) was obtained from in-situ/field permeability measurements (using the results of excess porewater pressure dissipation test) conducted in one of the CPT's.

Groundwater was encountered at elevations ranging from +2.0 m to -0.1 m. Due to the proximity of the roadway to ocean, groundwater level is expected to be influenced by tidal variations. For the analysis, groundwater was taken at elevation +2 m.

Embankment Staged Construction

As discussed previously, due to the presence of very soft organic clay deposit at shallow depth, the embankment would need to be constructed in stages/phases to maintain stability during construction. The staged construction stability analysis consisted of the following three iterative steps:

- Step 1 – Estimate the increase in undrained shear strength of the soft clay deposit due to consolidation under each additional fill and staging time by performing consolidation settlement and stress increase analyses.
- Step 2 – Perform global stability analysis using the updated undrained shear strength of the clay obtained in Step 1 and adjust the maximum additional fill thickness and staging time that can be safely placed on the existing slope, meeting the recommended minimum factor of safety guideline.
- Step 3 - Use the fill thickness estimated in Step 2 and reiterate both steps until convergence is obtained.

Incremental Strength Gain and Embankment Settlement

The computer program Settle3D (Rocscience Inc., 2017) [1] was used to estimate the anticipated excess porewater pressure dissipation, increases in effective

Table 1. Idealized Soil Profiles and Geotechnical Engineering Properties

Soil type	Bottom elevation (m)	γ_{sat} (kN/m^3)	φ (°)	S_u (kPa)	K (kPa/m)	ε_{50}	E_s (kPa)	OCR	C_c	C_r	C_v / C_{vr} (m^2/y)	e_0
Sand	-0.5	18.0	30	-	16,300	-	10,000	-	-	-	-	-
Soft clay	-9.0	18.0	-	20	-	0.02	-	1	0.8	0.2	3.2/12.6	2
Stiff clay	-16.0	18.5	-	150	271,000	0.005	-	2 to 5	0.3	0.1	3.2/12.6	0.9
Hard clay	-30.0	19.0	-	500	543,000	0.004	50,000	-	-	-	-	-

γ_{sat} – saturated unit weight, φ – friction angle, S_u – initial undrained shear strength, K – modulus of subgrade reaction, ε_{50} – strain at which one-half of the undrained strength is developed, E_s – elasticity modulus, OCR – over consolidation ratio, C_c – virgin compression index, C_r – recompression index, C_v / C_{vr} – coefficient of virgin consolidation/ reconsolidation, e_0 – initial void ratio

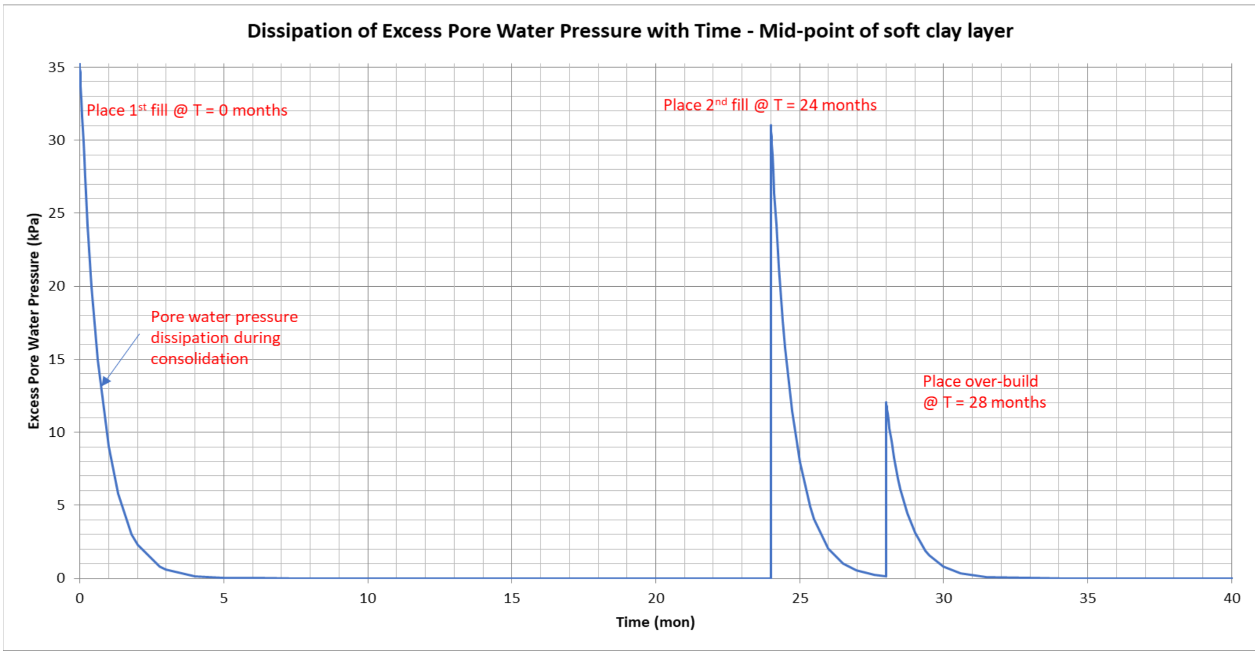


Figure 3. Dissipation of Excess Pore Water Pressure with Time During Fill Placements.

vertical stress and settlement with time and degree of consolidation within the soft clay deposit due to placement of each additional fill. The consolidation soil properties as presented in Table 1 were used for the analysis. Figure 3 depicts an example of excess pore water pressure dissipation with time during consolidation process as additional fills are placed.

To estimate the strength gain from the increase in effective vertical stress, an undrained shear strength to effective vertical stress ratio (S_u/σ'_v) of 0.29 was used. This ratio was selected based on the measured undrained shear strength increases with depth in the CPT soundings (see Figure 4, Panel a). These incremental shear strength gains were then added to the shear strengths obtained from the CPT's performed prior to any construction activities:

$$S_u\ (Stage\ i^{th}) = 0.29 * \Delta\sigma'_v\ (Stage\ i^{th}) +\ S_u\ (initial) \quad (1)$$

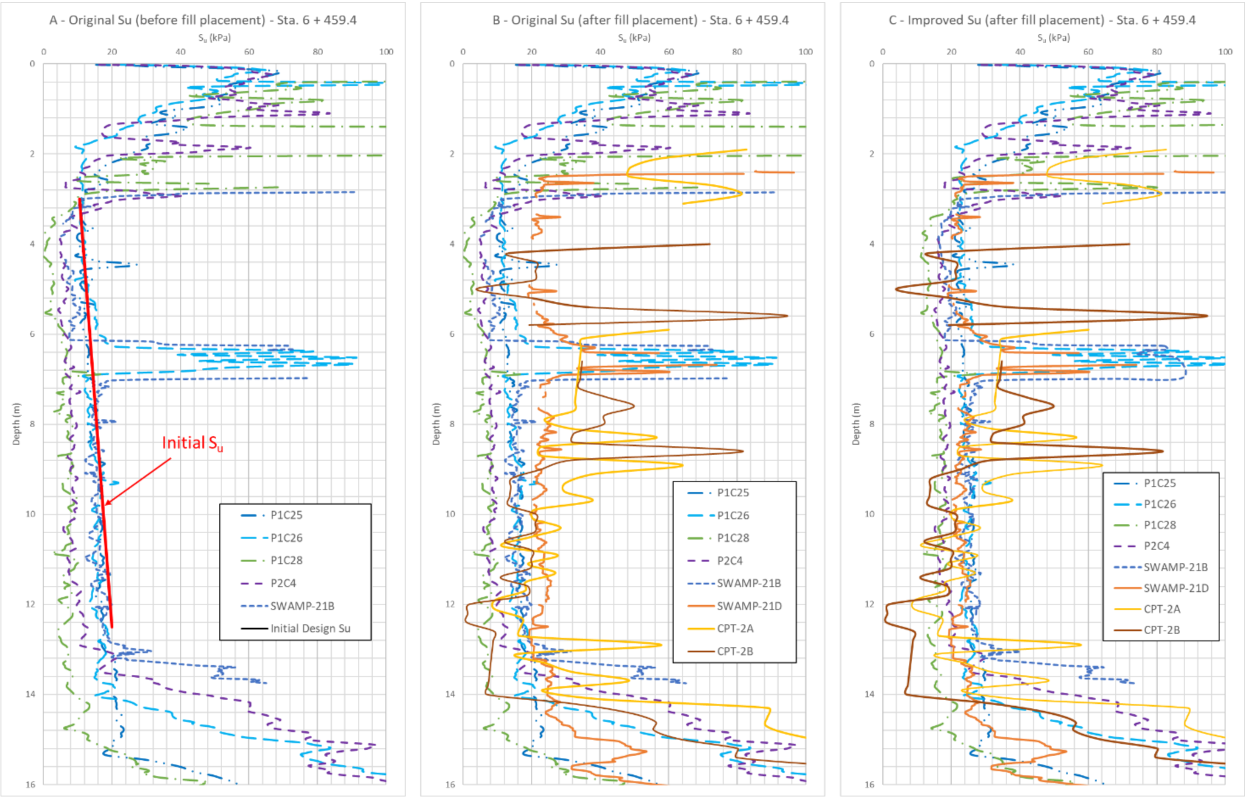
The values of $\Delta\sigma'_v$ at each construction stage were calculated at grid points within the soft clay deposit, consistent with the degrees of consolidation and excess pore water pressure dissipation that have taken place at these points. Therefore, higher strength increases were calculated for grid points closer to the top of clay deposit, where most of the drainage takes place.

Figure 4 shows the undrained shear strengths of the soft clay deposit before and after the fill placement. The solid lines on Panel b are the shear strengths obtained in CPT's that were pushed after the fill placement (i.e., after most of the consolidation process has taken place), showing increased shear strengths as compared to those obtained in CPT's performed prior to fill placement. Panel c compares the adjusted undrained shear strengths after applying the strength increases/gains, as predicted by Eq. 1, to the initial shear strengths. The comparison shows a good agreement between the predicted and measured values after placement of fills.

The incremental settlements as the results of soft clay consolidation due to fill placement were calculated at each stage of construction, and they were included in the fill height and placement fill thickness for the subsequent construction stages, as described below.

Fill Placement Schedule

Using the settlement-adjusted embankment geometry and increased clay shear strength, the maximum fill thickness that can be safely placed in the next stage was calculated in a slope stability analysis using the computer program SLIDE (Rocscience Inc., 2017) [2]. To help accelerating the consolidation process,



(a) (b) (c)

Figure 4. (a) Estimated Undrained Shear Strengths Prior to Fill Placement, (b) Comparison of Initial Undrained Shear Strengths with Those Estimated After Fill Placement, and (c) Comparison of Adjusted Undrained Shear Strengths with Those Estimated After Fill Placement.

wick drains were installed down to the top of stiff clay layer at a 1.2-m triangular spacing. With wick drains, the time required for the completion of 95% primary consolidation in the soft clay layer, t_{95}, was estimated to be 3 to 4 months.

Table 2 presents the recommended fill placement thickness and waiting/staging time for each construction stage before subsequent fill can be safely placed at the abutment location. Stability at the end-of-construction (EOC) for each of the construction stages, as presented in Table 2, was analyzed using the updated geometry (after adjusting for settlements induced in previous stages) and undrained soil strength. For the final abutment configuration, the long-term stability of the roadway embankment was also analyzed using both the updated undrained and drained strengths.

Table 2. Fill Placement Schedule at Abutment

Stage No.	Fill Thickness (m)	Time (Months)	Construction Considerations
1	1.5	0	Install wick drains at 1.2 m spacing prior to placing fill.
2	1.5	3	3 month waiting period before the second lift of fill can be placed
3	1.2	6	Additional 3 month waiting period before the third lift of fill can be placed
4[a]	0.8	9	Additional 3 month waiting period before the last lift of fill can be placed. Complete final grading and pavement sections; construct abutment walls and fills

[a] Total fill thickness of 5.5m, includes overbuilt thickness to compensate for settlements from previous stages

Table 3 summarizes the loading scenarios analyzed, calculated factors of safety for each loading case and the minimum recommended factors of safety. Live or traffic loads of 6 and 12 kPa were used for during-construction and long-term loading conditions, respectively. The recommended minimum factors of safety for embankment stability at EOC and long-term loading conditions are 1.25 and 1.50, respectively. As can be seen from the table, the calculated factors of safety at the abutment for the various construction stages meet or exceed the minimum values (factor of safety in Stage 3 is slightly less than 1.25, which is considered acceptable).

Figures 5 and 6 illustrate the critical sliding surfaces and their corresponding factors of safety at the end of construction stages 2 and 3. The existing piles supporting the bridge abutment were included in the models.

Settlement-induced Down-drag and Lateral Squeeze on Piles

The bridge abutments are supported on bored piles that extend through the soft compressible clayey soils. Placement of fills will displace soil vertically (settlement) and laterally (lateral squeeze). These soil movements have the potential to overstress the piles during construction, causing the abutment to tilt away from the fill and damages to the piles. The settlement produces down-drag forces along the piles above the compressible soil, and these additional forces could compromise the pile structural integrity and/or induce excessive pile settlement. The existing piles were evaluated for the down-drag forces, and they were found to be satisfactory.

Table 3. Summary of Global Slope Stability Analyses

Scenario No.	Loading Details	Waiting Time (months)	Soft Clay Strength	Calculated FS		Recommended Minimum FS
				North	Median	
Construction Stage 1	1.5m fill placed above existing ground surface; LL = 6 kPa	3	S_u = 20kPa	1.91	1.69	1.25
Construction Stage 2	Additional 1.5m fill lift placed above Stage 1; LL = 6 kPa	3	S_u includes 95% consolidation under Stage 1 fill	1.50	1.39	1.25
Construction Stage 3	Additional 1.2m fill lift placed above Stage 2; LL = 6 kPa	3	S_u includes 95% consolidation under Stage 2 fill	1.33	1.24	1.25
Construction Stage 4	0.8m pavement layer placed above Stage 3; LL = 6 kPa	3	S_u includes 95% consolidation under Stage 3 fill	1.46	1.37	1.25
Case 5	Long-term condition; LL = 12 kPa	N/A	S_u includes Full consolidation under entire 5.5m fill	2.35	2.20	1.50
Case 6	Long-term condition; LL = 12 kPa	N/A	Drained shear strength	3.01	2.79	1.50

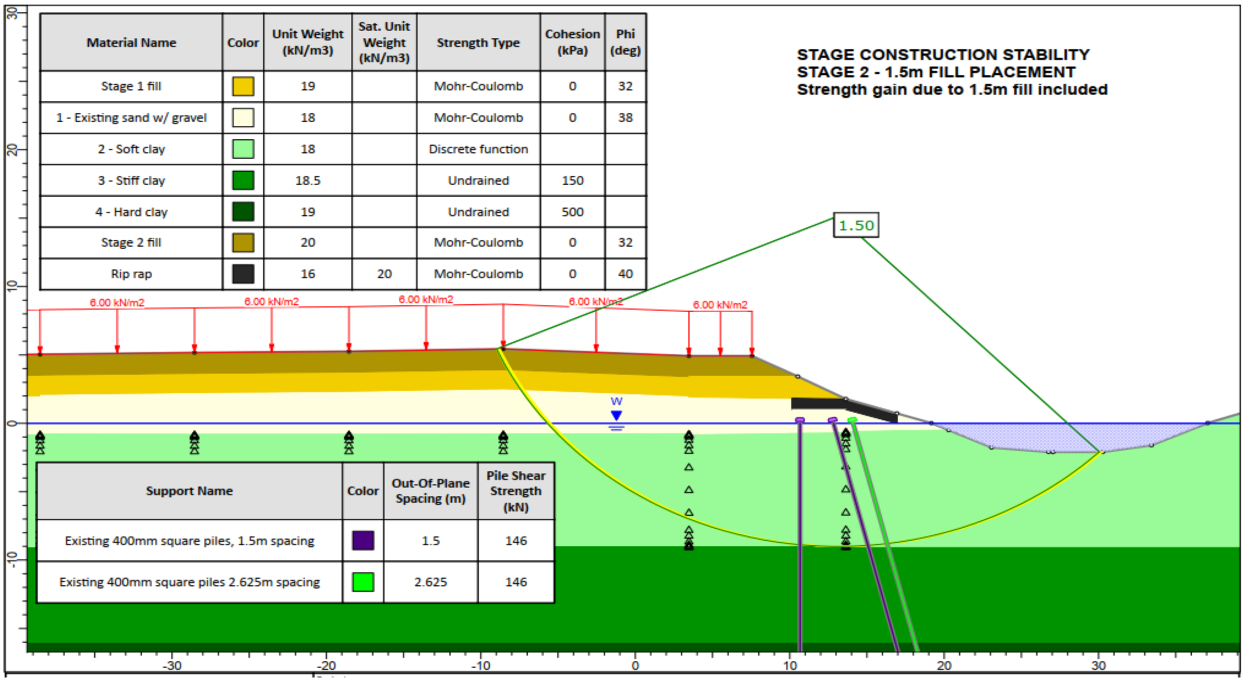
FS – Factor of Safety, EOC – End of Construction, LL – traffic and/or construction equipment Live loads

The potential for lateral squeeze was first evaluated using the procedure presented in the Federal Highway Administration (FHWA) NHI-05-042 publication (FHWA, 2006) [3]. Per the FHWA guidelines, the abutment tilting would likely occur if the following condition governs:

$$\gamma_f * h_f > 3 * S_u$$

Where, γ_f is the unit weight of fill, h_f is the total height of fill placed and S_u is the undrained shear strength of the soft clays. Based on the above criteria, there is low to moderate potential for lateral squeeze on the bridge abutment piles. To further evaluate the potential for roadway fill induced lateral squeeze, a two-step procedure as described below was employed:

- Lateral forces exerted on the piles were obtained from the slope stability analyses. It was conservatively assumed that the entire roadway fill was placed in one single stage and abutment slope instability was assessed immediately after the placement of the fill, thus allowing no strength gain in the soft clay layer. A factor of safety less

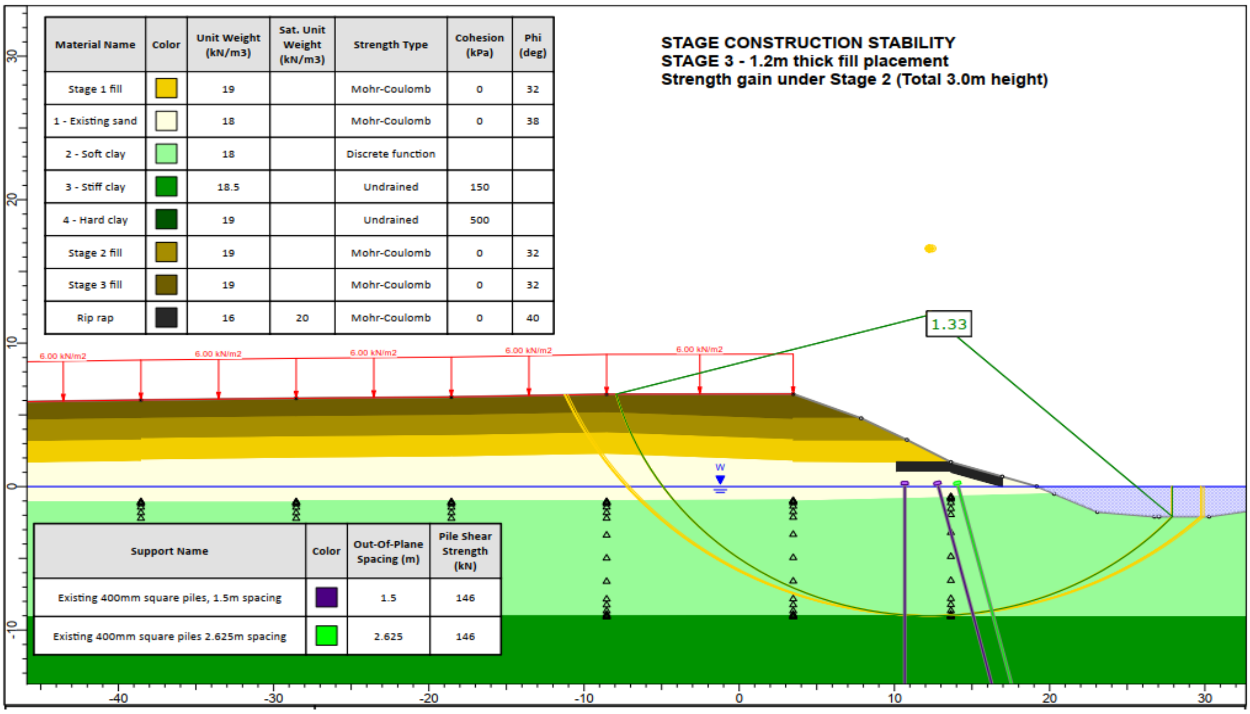


Material Name	Color	Unit Weight (kN/m3)	Sat. Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)
Stage 1 fill	🟨	19		Mohr-Coulomb	0	32
1 - Existing sand w/ gravel	⬜	18		Mohr-Coulomb	0	38
2 - Soft clay	🟩	18		Discrete function		
3 - Stiff clay	🟩	18.5		Undrained	150	
4 - Hard clay	🟩	19		Undrained	500	
Stage 2 fill	🟫	20		Mohr-Coulomb	0	32
Rip rap	⬛	16	20	Mohr-Coulomb	0	40

Support Name	Color	Out-Of-Plane Spacing (m)	Pile Shear Strength (kN)
Existing 400mm square piles, 1.5m spacing	🟪	1.5	146
Existing 400mm square piles 2.625m spacing	🟩	2.625	146

STAGE CONSTRUCTION STABILITY
STAGE 2 - 1.5m FILL PLACEMENT
Strength gain due to 1.5m fill included

Figure 5. Critical Sliding Surface and Calculated Factor of Safety During Construction Stage 2 (North Side)



Material Name	Color	Unit Weight (kN/m3)	Sat. Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)
Stage 1 fill	🟨	19		Mohr-Coulomb	0	32
1 - Existing sand	⬜	18		Mohr-Coulomb	0	38
2 - Soft clay	🟩	18		Discrete function		
3 - Stiff clay	🟩	18.5		Undrained	150	
4 - Hard clay	🟩	19		Undrained	500	
Stage 2 fill	🟫	19		Mohr-Coulomb	0	32
Stage 3 fill	🟫	19		Mohr-Coulomb	0	32
Rip rap	⬛	16	20	Mohr-Coulomb	0	40

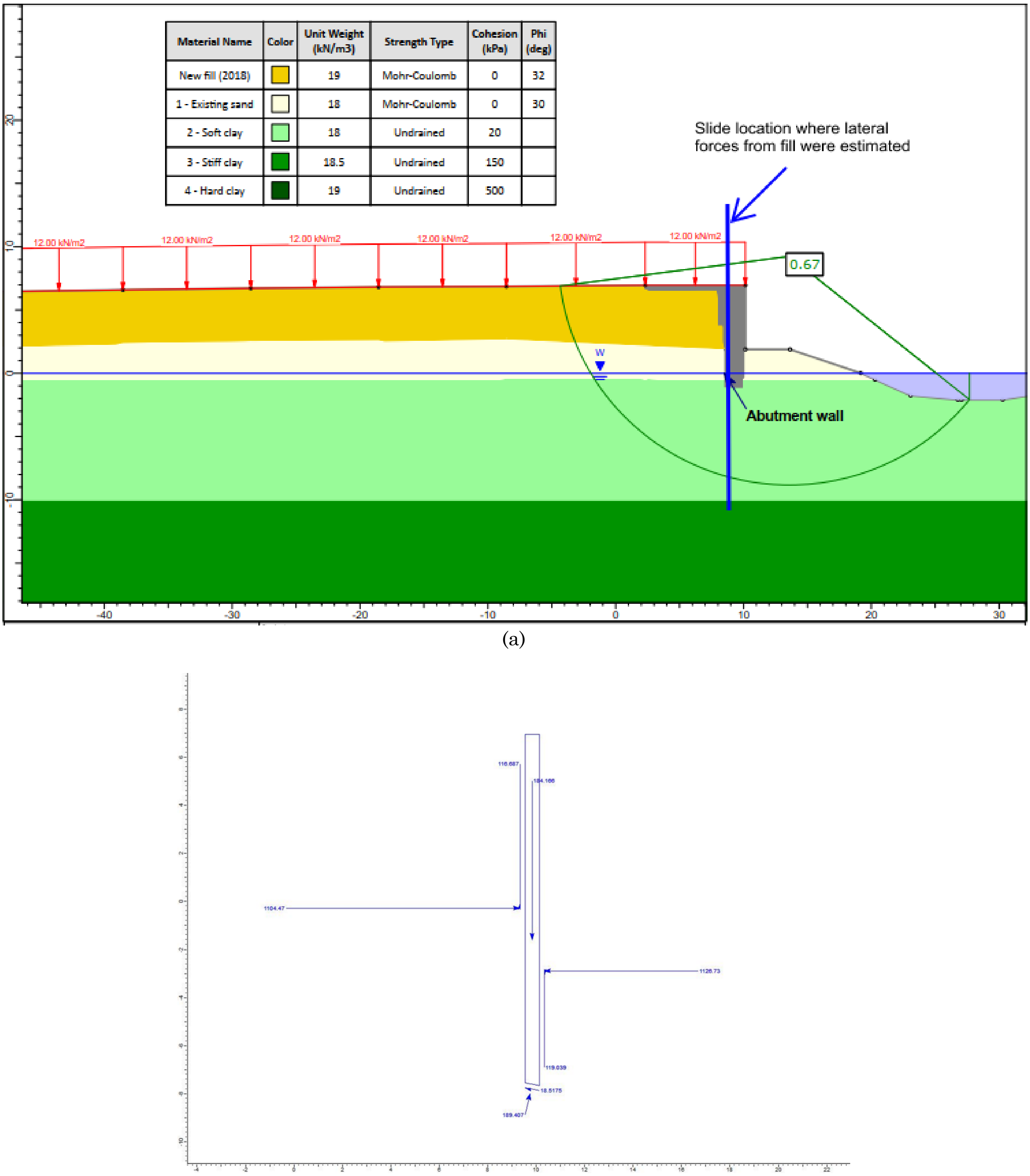
Support Name	Color	Out-Of-Plane Spacing (m)	Pile Shear Strength (kN)
Existing 400mm square piles, 1.5m spacing	🟪	1.5	146
Existing 400mm square piles 2.625m spacing	🟩	2.625	146

STAGE CONSTRUCTION STABILITY
STAGE 3 - 1.2m thick fill placement
Strength gain under Stage 2 (Total 3.0m height)

Figure 6. Critical Sliding Surface and Calculated Factor of Safety During Construction Stage 3 (North Side)

than 1.0 for this scenario was calculated, indicating that the abutment slope is unstable under the entire roadway fill without the piles. Figures 7a and 7b show the location and slide forces, respectively, obtained from the slope stability analysis.

- Lateral-loaded pile analyses were then conducted using the computer program LPILE (Ensoft, Inc., 2016) [4] to estimate the pile deflections, shear forces and moments induced by the lateral forces from the fill. Under a pinned-head condition, the roadway fill induces a lateral displacement at the pile head of about 7 to 11 millimeters. Maximum shear force and bending moment induced by the roadway fill are 129 kN and 751 kN-m, respectively. Figure 8 plots the calculated deflections, shear forces and bending moments along the pile. The pile structural capacities were then evaluated under these induced forces.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)
New fill (2018)	🟨	19	Mohr-Coulomb	0	32
1 - Existing sand	⬜	18	Mohr-Coulomb	0	30
2 - Soft clay	🟩	18	Undrained	20	
3 - Stiff clay	🟩	18.5	Undrained	150	
4 - Hard clay	🟩	19	Undrained	500	

Slide location where lateral forces from fill were estimated

Abutment wall

(a)

(b)

Figure 7. (a) Location where Slide Forces were obtained and (b) Lateral Slide Forces Estimated for Slope Stability Analysis

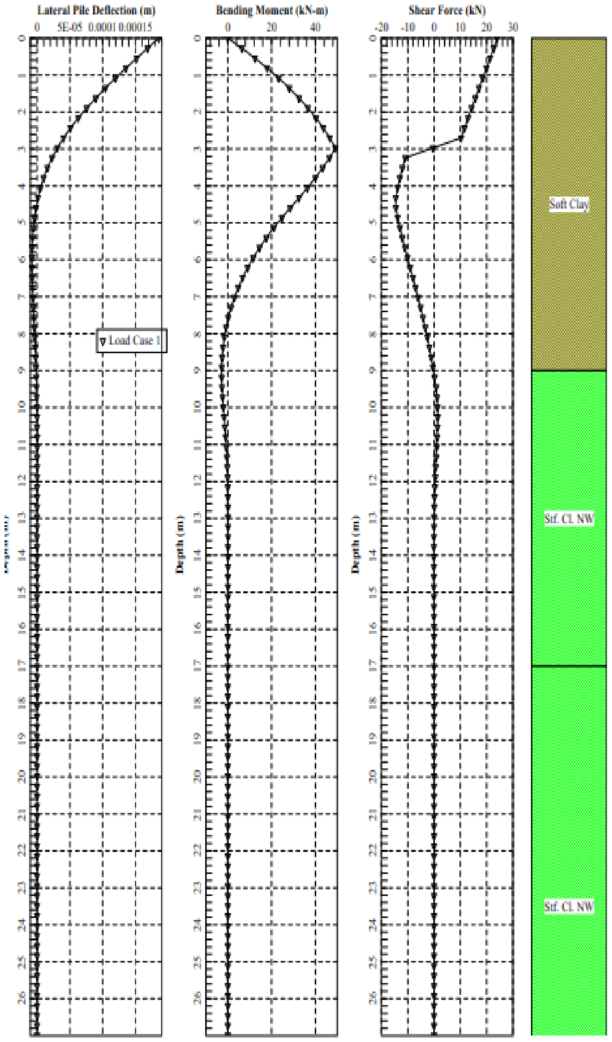


Figure 8. Calculated Pile Deflection and Forces due to Soil Lateral Squeeze

Conclusions

Roadway construction on soft ground (clayey soils) faces major challenges due to instability and excessive settlements following placement of roadway embankment fill. In remote regions, mitigations that include installation of wick drains and preload to accelerate soil consolidation process, ground improvement to increase soil's strength and stiffness, and/or installation of geogrids to reinforce soils and distribute loads could be costly or simply not readily available.

An alternative construction method, whereby the roadway embankment is constructed in phases to allow partial consolidation of clayey soils to take place before additional embankment fill can be safely placed, is proposed. At each construction phase, the additional fill thickness and staging time are determined, and the corresponding degrees of consolidation and incremental strength gains are calculated within the soft organic clay. The stability of the partially built embankment is then evaluated, and the fill thickness and staging time are adjusted to meet the stability safety requirements. The impacts of soil movements due to fill placement to pile foundation are also evaluated to ensure that the pile integrity will not be compromised.

References

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2. Rocscience Inc., Slide, Version 7.028, 2017.
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