Case History: Finite Element Analysis of Time Dependent Settlement of Lake Jessup Bridge Embankment in Central Florida

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ABSTRACT

Finite Element Analysis (FEA) was performed to evaluate the settlement of the three-stage approach embankment of Lake Jessup Bridge in Central Florida. The subsoil matrix was mainly sandy soils with embedded clayey layers. Classical elastic and time dependent settlement analysis could not accurately capture settlement during construction stages. Two-dimensional FEA were performed utilizing Mohr-Coulomb and Soft Soil Creep models. Both models were able to capture settlement at different stages of construction, however, the Soft Soil Creep model provided better estimations for the long term pore water pressure dissipation profile. Settlement plates were installed to monitor the in-field settlement during and after construction close to the location of the embankment full height. The monitoring program continued for 8 months, at which, settlement rates substantially decreased. The recorded settlements were in agreement with the settlement profile predicted using the FEA. The presented case history showed that FEA provided better simulation of subsoil conditions, boundary conditions, loading conditions, and construction sequence and stages as compared to classical methods.

INTRODUCTION

Geotechnically, typical roadway design projects usually include roadway, bridges, approaching embankments, culverts or similar structures, and temporary or permanent retaining/sheet pile walls. Approach embankments usually constructed with natural slopes of a 2:1 slope, however, if the right of way is limited, retaining walls are needed. Mechanically Stabilized Earth (MSE) walls are the most popular retaining system utilized in approach embankments in Central Florida. Most of the bridges in Central Florida are supported on deep foundations in the form of driven piles, which, minimizes the bridge settlement, however, the embankment sections, especially closer to the bridge abutment, are supported on natural soil, hence, will experience considerable settlement. Differential settlement between the end of the embankment section and the start of the bridge section of the road is usually of concern to the structural and geotechnical engineer.

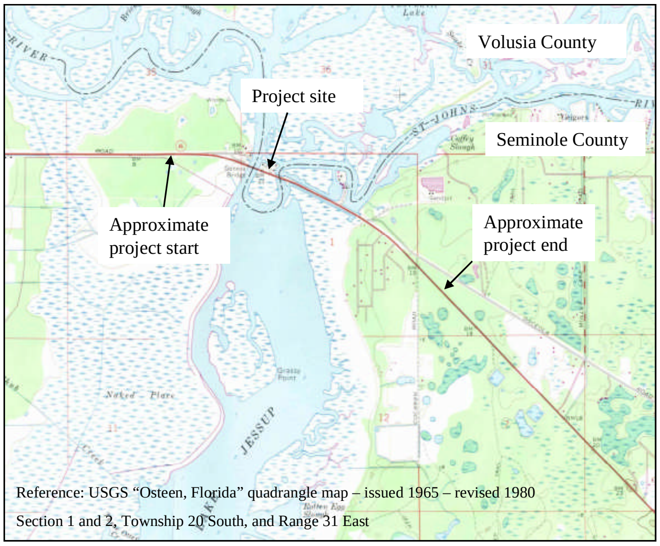
Settlement of the roadway embankments, which includes elastic, end of primary consolidation, and secondary consolidation settlements, is usually estimated using hand calculations using classical methods; elastic theory for immediate settlement and Terzaghi's one dimensional consolidation theory for time dependent settlement. The subsoil conditions have to be idealized into successive horizontal layers with uniform strength and compressibility parameters. Contact pressures are usually assumed to be uniformly distributed. The use of FEA to model the subsoil, groundwater, and loading conditions provides a more realistic solution. Non-homogeneity of the foundation soil, anomalies, boundary conditions, loading conditions, and loading sequence can be modeled. The behavior of the foundation soil can be captured using a variety of soil constitutive models available in most FEA packages.

The case history presented in this paper presents the results of a detailed settlement analysis for the approach embankment of the Lake Jessup Bridge in Central Florida. The subsoil matrix at the embankment site was mostly sandy with two layers of clayey material. The embankment was built in three stages and left in place for few months before being opened for traffic. Settlement was estimated using FEA taking into account the unique construction stages. In-field settlement was monitored and was found to be in good agreement with he predicted values.

PRESENTED CASE HISTORY

Location and Description

The project site is located in Seminole County at the border with Volusia County as shown on Figure 1. The existing SR46 bridge over Lake Jessup was to be replaced by a new bridge with a total length of approximately 1128 m. Due to the right of way constraints at the west bridge approach, MSE wall was planned along the south portion of the alignment. The maximum height of the proposed approach embankment was 7.9 m and consisted of three stages and will be constructed as follows; i) A 2.25 m high earth embankment with 2H:1V slopes to be constructed in one month, ii) A 5.0 m high MSE wall to be constructed in three months, and iii) A 1.14 m high earth embankment with 2H:1V slopes to be constructed in one month.



Reference: USGS "Osteen, Florida" quadrangle map – issued 1965 – revised 1980

Section 1 and 2, Township 20 South, and Range 31 East

Figure 1. Project location and limits projected on the USGS quadrangle map

Geotechnical Engineering Study

The field work performed within the higher portion of the embankment included six Standard Penetration Test (SPT) borings drilled to depths of 12 to 21 m. Four Shelby tubes were extracted to provide undisturbed samples for strength and compressibility tests. The results of the consolidation tests are summarized in Table 1. Other laboratory tests included routine index tests to help classify the subsoil conditions and establish the stratigraphy. Details of the encountered subsoil and groundwater conditions, the results of the index laboratory tests, and the recorded SPT N-values are show on Figure 2.

Table 1. Summary of the laboratory test results

Boring	Shelby tube depth, m	Compression Index	Swelleing Index	Initial void ratio	Preconsolidation pressure, KPa	Dry unit weight, KN/m^3	Liquid Limit, %	Plastic Limit, %
TH-1*	3.2 - 3.8	0.54	0.21	1.57	198	10.33	70	23
TH-2*	3.5 - 4.1	0.71	0.22	1.79	192	9.44	95	30
TH-2*	5.5 - 6.1	0.27	0.1	1.01	192	13.36	73	21
TB-9a	6 - 6.6	0.42	0.1	1.144	142	12.54	73.5	54.5
TB-27a	2.1 - 2.7	0.24	0.04	0.791	120	14.87	45.5	30.4

* Results of these tests were provided to the authors by the PD&E geotechnical consultant

Hand Calculations Using Classical Methods

Soil parameters needed to perform the settlement analysis were estimated utilizing some of the published correlations to the recorded N-values in combination with the laboratory test results. Table 2 summarizes the idealized subsoil stratification system used to estimate initial and time dependent settlements. Schmertman's method was used to estimate initial settlement, whereas Terzaghi' theory of one dimensional consolidation was used to estimate time dependent settlement. The results of the settlement analysis are summarized in Table 3. Although final settlements were estimated and a settlement-time relationship was predicted, settlement during construction phases and the corresponding strength gain was not captured. Previous experience of the authors at nearby site locations for similar loading conditions suggested that the classical solutions over-predicted future settlement.

Table 2. Idealized subsoil conditions and stratification system

Property	Units	Embankment	I	II	III	IV	V
		Sandy Fill	Sand	Clay	Sand	Clay	Silty to clayey sand
Depth to top, m		N/A	0	0.3	3.65	4.25	7.3
Depth to bottom, m			0.3	3.65	4.25	7.3	23
Thickness, m			0.3	3.35	0.6	3.05	15.7
γ_{unsat}	KN/m^3	17.75	16.9	18.22	16.97	18.22	18
γ_{sat}	KN/m^3	N/A	19.95	18.38	19.95	18.38	20
E	Mpa	N/A	11.5	23.94	11.5	23.94	20
ν	N/A	N/A	0.3	0.3	0.3	0.3	0.3
c_u	Kpa	N/A	N/A	65.6	N/A	65.6	0
φ	degree	N/A	32	0	33	5	35
c_c	N/A	N/A	N/A	0.4725	N/A	0.295	N/A
c_s	N/A	N/A	N/A	0.14	N/A	0.06	N/A
σ_c	N/A	N/A	N/A	278	N/A	288	N/A
e_0	N/A	N/A	N/A	1.68	N/A	1.01	N/A

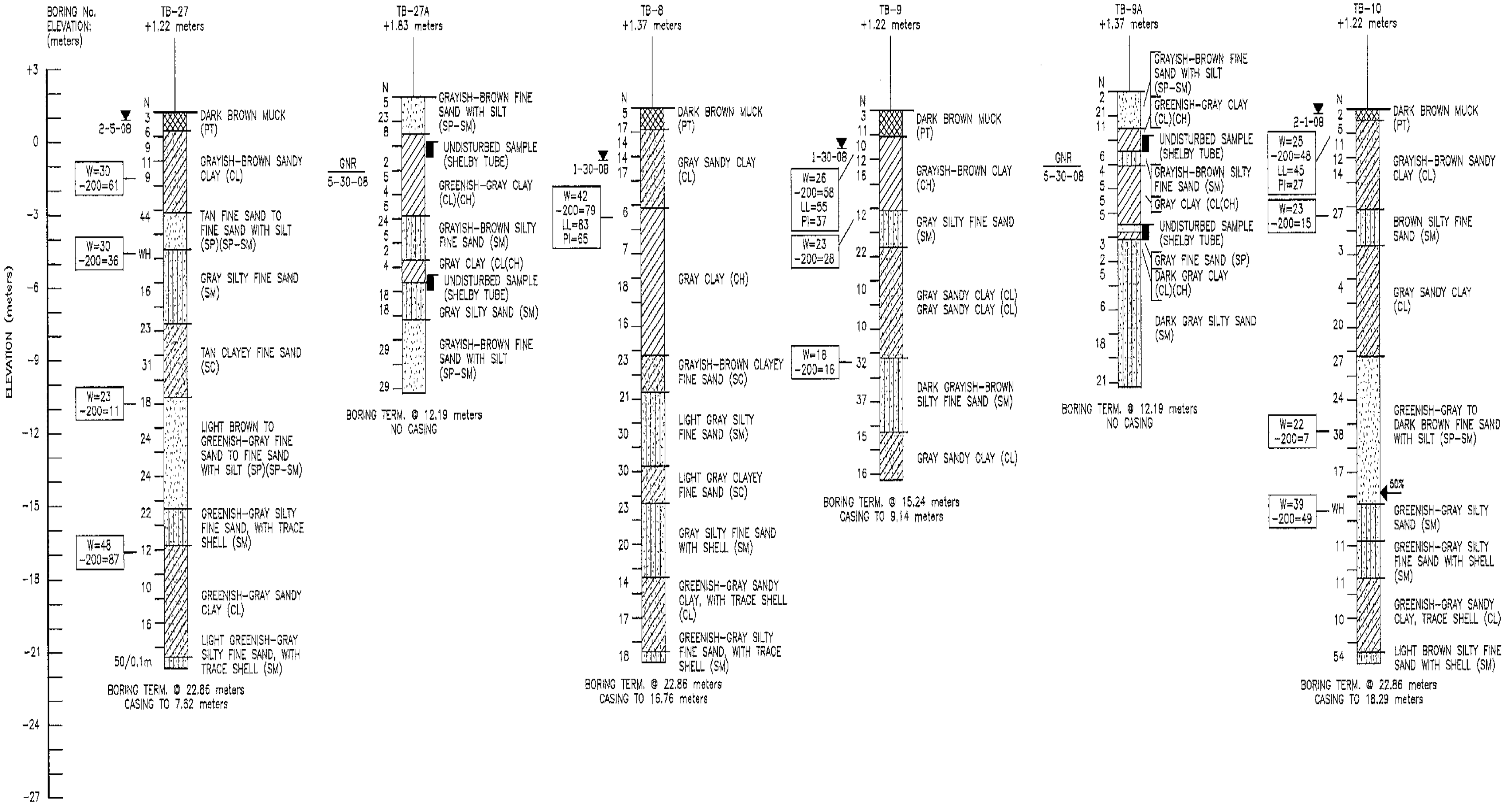


Figure 2. Details of the subsoil and groundwater conditions at the west approach embankment along with laboratory test results and the recorded SPT N-values

Table 3. Results of settlement analysis using classical methods

Type of settlement	Estimated values, m
Initial/elastic/primary settlement	0.038
End of primary consolidation settlement	0.137
Total Settlement not including secondary settlement	0.175
Secondary consolidation settlement after 75 years	0.076
Total Settlement	0.251

Finite Element Analysis (FEA)

FEA is a needed tool for geotechnical engineers to perform rigorous stress-strain analysis, which usually results in more realistic settlement estimates leading to substantial cost savings. FEA may be utilized in almost every aspect of geotechnical engineering such as settlement predictions, bearing capacity of shallow footings and mat foundations, analysis of axially and laterally loaded single vertical, battered pile, pile groups, and drilled shafts, staged construction of embankments for highways and railroads, deep excavations in several stages, analysis and design of earth retaining structures, global slope stability, and tunnel and mine construction.

FEA provides the geotechnical engineer with variety of features such as; the ability to virtually model any shape in both 2D and 3D, specific elements to model soil-structure interaction, various analysis types, and advanced non-linear soil models, which may capture most aspects of soil stress-strain behavior. Available models includes Mohr Coulomb, Modified Mohr Coulomb, Modified Cam Clay, Strain Hardening, Strain Softening, Soft Soil Creep, Soft Soil, and Linear Elastic. Currently, many FEA software packages are available for the geotechnical engineers and have been used in day-to-day calculations by many geotechnical designers.

The authors have been using the FEA package “PLAXIS” for the last 5 years to model and evaluate foundation systems and other application throughout Central Florida. The authors’ combined 50+ years experience in Central Florida allowed for comparing the results of numerical modeling to actual monitoring results, which helped to refine soil parameters used in FEA for most Central Florida soils.

FEA Utilizing Mohr-Coulomb Model

The first round of the FEA was performed utilizing Mohr-Coulomb (MC) model for the idealized system including the clays. The MC model is an elastic-plastic model, which is defined using E and ν for elasticity, c and φ for plasticity, and ψ for dilatancy. It is a first-order approximation model. The soil average stiffness is constant and computation time is fast as compared to more advanced models.

Consolidation analysis was used to simulate the construction stages. This options allows the calculation of settlement and strength gain during construction by assigning a construction time, through which, the load will be gradually applied. Figure 3 shows the model geometry at the final stage of the embankment construction. Table 4 summarizes the soil parameters of the idealized stratification system. A Denser finite element mesh was used for the two clay layers in order to capture the pore water pressure (PWP) dissipation and the corresponding consolidation settlement.

Figure 4 shows settlement estimates for the modeled stages, which included; first embankment, MSE wall, second embankment, time to open the roadway to traffic, and after 75 years of the road being in service. Three main points below the center of the embankment were tracked during the analysis; Point A at the ground surface, Point B at the center of the top clayey layer, and Point C at the center of deeper clayey layer. Figure 5 shows the settlement–time relationship for Point A, which shows that settlement should stabilize after about 150 days and the maximum settlement should be in the order of 0.15 m. Figure 6 shows the PWP dissipation at Points B and C, which showed the excess PWP to totally dissipate after about 200 days. It should be noted that the FEA model estimated negative excess PWP between 200 and 490 days, which the authors could not explain, hence decided to carry out the FEA using a higher level soil model for the clayey deposits in order to better describe the dissipation of the PWP.

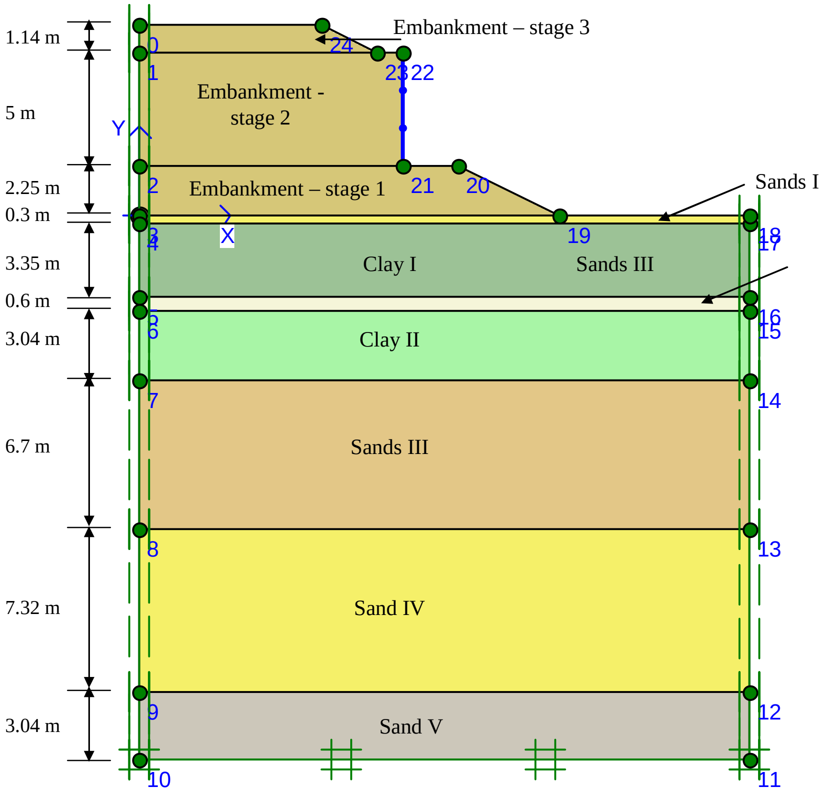


Figure 3. Mohr-Coulomb analysis – Model geometry

Table 4. Soil parameters for the idealized stratification system of the FEA model

Property	Units	Embankment	Sand I	Clay I	Sand II	Clay II	Sand III	Sand IV	Sand V
		Drained	Drained	Undrained	Drained	Undrained	Drained	Drained	Drained
γ_{unsat}	KN/m^3	17.75	16.97	18.22	16.97	18.22	17.75	18.85	23.25
γ_{sat}	KN/m^3	20.42	19.95	18.38	19.95	18.38	20.42	20.89	23.4
k_x	m/day	0.91	1	8.53E-05	1	8.53E-05	0.3	0.3	1
k_y	m/day	0.91	1	8.53E-05	1	8.53E-05	0.3	0.3	1
E_{ref}	Mpa	13.8	11.5	23.94	11.5	23.94	13.8	16.85	30.6
ν	N/A	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
c_{ref}	Kpa	2.4	2.4	65.6	2.4	65.6	0.5	0.5	0.5
φ	degree	33	32	0	32	0	33	35	40
ψ	degree	0	0	0	0	0	0	0	0

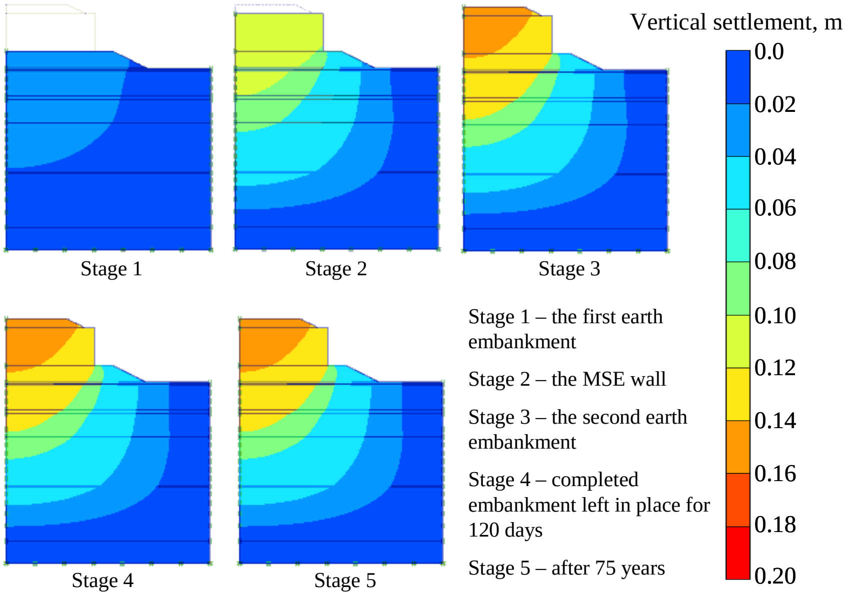


Figure 4. MC analysis – settlement contours for successive construction stages

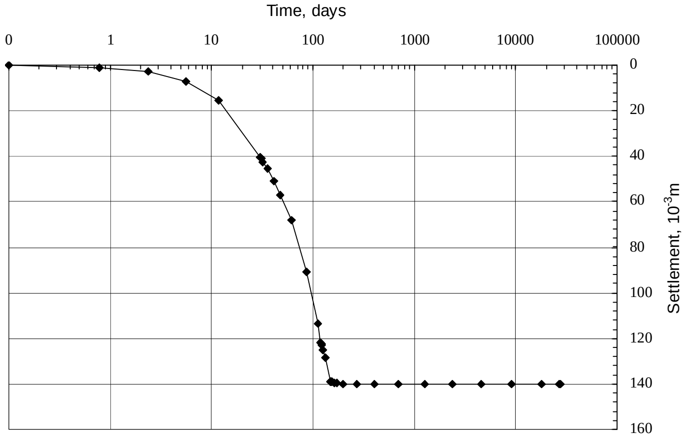


Figure 5. MC analysis – Settlement log-time relationship for Point A

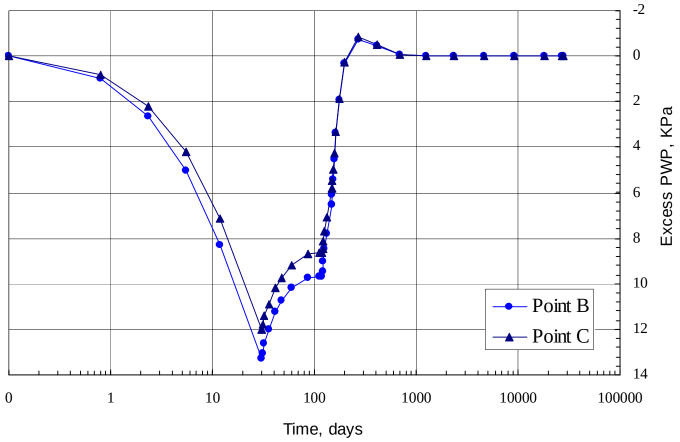


Figure 6. MC analysis – PWP dissipation for Points B and C

FEA Utilizing Soft Soil Creep Model

The FEA was repeated for the same model geometry, boundary conditions, and loading stages, however, the Soft Soil Creep (SSC) model was used to model the clays deposits. SSC is a second-order model formulated in the framework of visco-plasticity. It can be used to model the time-dependent behavior of soft soils like NC clays and peat and performs best in situations of primary and secondary consolidation. Table 5 summarizes the soil parameters for the idealized stratification system. Figure 7 shows settlement estimates for the modeled stages. Three main points below the center of the embankment were tracked during the analysis; Point D at the ground surface, Point E at the center of the top clayey layer, and Point F at the center of deeper clayey layer. Figure 8 shows the settlement–time relationship for Point D, which shows that settlement continues to increase throughout the modeled period (75 years), however, the rate of increase decreased substantially after 9 months and the maximum settlement should be in the order of 0.17 m. Figure 9 shows the PWP dissipation at Points E and F, which showed the excess PWP to totally dissipate after about 11 years. No negative excess PWP was estimated during this round of the FEA.

Table 5. SSC analysis - Soil parameters for the idealized stratification system

Property	Units	Embankment	Sand I	Clay I	Sand II	Clay II	Sand III	Sand IV	Hawthorne
		Drained	Drained	Undrained	Drained	Undrained	Drained	Drained	Drained
γ_{unsat}	KN/m^3	17.75	16.97	18.22	16.97	18.22	17.75	18.85	23.25
γ_{sat}	KN/m^3	20.42	19.95	18.38	19.95	18.38	20.42	20.89	23.4
k_x	m/day	0.91	1	8.53E-05	1	8.53E-05	0.3	0.3	1
k_y	m/day	0.91	1	8.53E-05	1	8.53E-05	0.3	0.3	1
E_{ref}	Mpa	13.8	11.5	23.94	11.5	23.94	13.8	16.85	30.6
ν	N/A	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
c_{ref}	Kpa	2.4	2.4	65.6	2.4	65.6	0.5	0.5	0.5
φ	degree	33	32	5	32	5	33	35	40
ψ	degree	0	0	0	0	0	0	0	0
c_c	N/A	N/A	N/A	0.4725	N/A	0.295	N/A	N/A	N/A
c_s	N/A			0.1		0.06			
c_α	N/A			0.012		0.0075			
$e_{initial}$	N/A			1.68		1.01			

Settlement Monitoring Program

In order to verify and confirm the settlement estimates of both the hand calculations and the FEA model, a total number of eight settlement plates were installed and monitored. The settlement plates were installed close to the full height portion of the embankment. The locations and elevations of the settlement plates were surveyed by a professional surveyor. Figure 10 shows time-settlement curves plotted for the individual settlement plates as well as the average readings of all eight plates. The approximate construction stages are also shown on the time-settlement curves, which account for the pronounced settlement increases. After about 222 days, which included about 180 days of construction, total settlements in the order of 0.20 m to 0.25 m were recorded with an average value of about 0.22 inches as compared to a total settlement of 0.175 using hand calculations (end of primary) and about 0.14 using FEA at about 220 days. The last three readings at 190, 205, and 222 days showed that the rate of settlement have substantially decreased substantially.

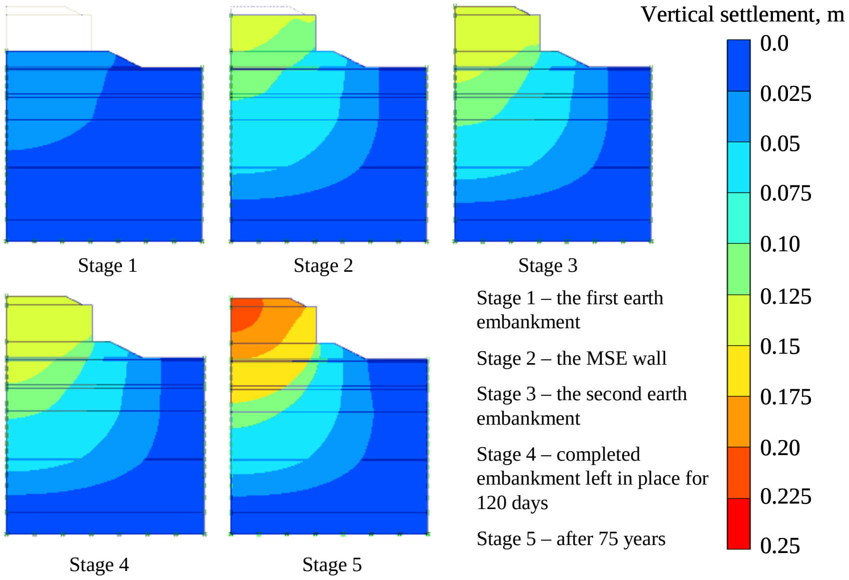


Figure 7. SCC analysis – settlement contours for successive construction stages

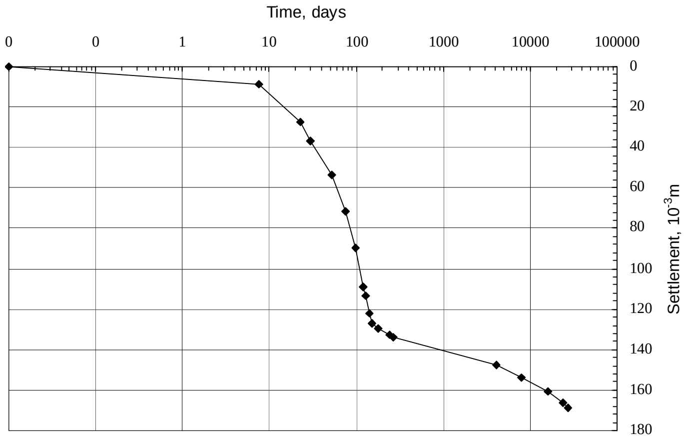


Figure 8. SCC analysis – Settlement time relationship for Point D

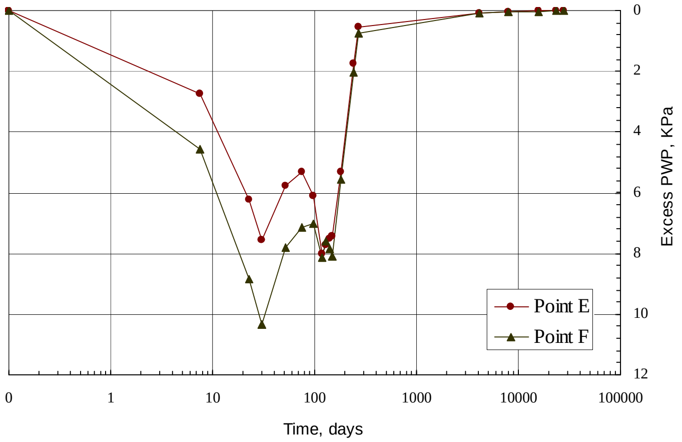


Figure 9. SCC analysis – PWP dissipation for Points E and F

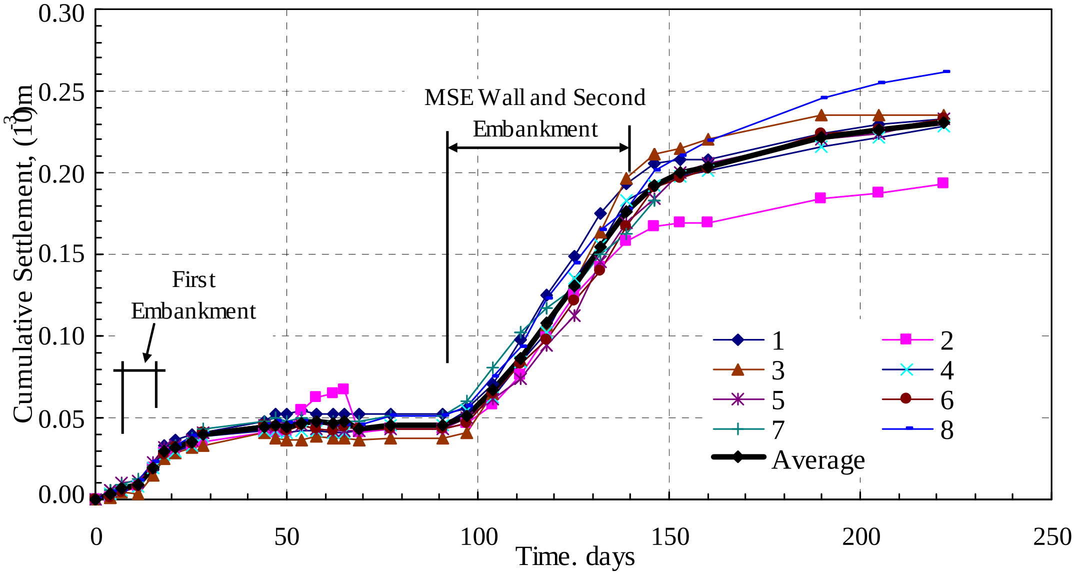


Figure 9. Plot of settlement versus time during the monitoring period

CONCLUSIONS

A settlement analysis for a three-stage approach embankment of Lake Jessup Bridge in Central Florida was performed using Finite Element Analysis. The subsoil conditions included two clay layers interbedded between sandy layers. Undisturbed samples were collected and consolidation tests were performed along with index tests to evaluate the subsoil stratification system. Hand calculations using classical methods could not capture settlement and stress gain occured during construction stages. FEA using the software PLAXIS was performed utilizing both Mohr-Coulomb (MC) and Soft Soil Creep (SCC) models to capture the behavior of the clays. Settlement estimates were similar using both models, however, SCC model provided better description of the PWP dissipation throughout the modeled 75 years. Settlement plates were installed and monitored to verify and confirm the estimated settlements. The results showed agreement between the estimated and monitored settlement values. The authors recommend using SCC model or similar high order models when analyzing long term settlement of soft clays or organics.

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