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Application of Finite Element Method for the Assessment and Comparative Analysis of Embankment Consolidation

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Abstract

The long-term performance of highway embankments constructed on compressible soils is significantly influenced by consolidation settlement and deformation characteristics of the underlying foundation soils. Conventional analytical approaches such as Terzaghi's one-dimensional consolidation theory are widely used for settlement prediction; however, these methods are limited in representing complex subsurface conditions and realistic field behavior. This study therefore assessed embankment consolidation behavior using both Terzaghi's analytical method and the Finite Element Method (FEM) implemented in PLAXIS 2D within the Ewu Hill section of the Benin-Auchi Expressway. Representative geotechnical datasets comprising moisture content, Atterberg limits, permeability, compression index, coefficient of consolidation, cohesion, and friction angle were obtained from published geotechnical investigations and documented embankment studies within humid tropical environments of Southern Nigeria. Terzaghi's analytical consolidation procedure was applied to estimate settlement magnitude and consolidation rate, while FEM simulation was conducted using coupled hydro-mechanical analysis in PLAXIS 2D to evaluate stress redistribution, pore water pressure dissipation, deformation behavior, and long-term embankment performance. The results revealed that settlement increased progressively with time due to gradual dissipation of excess pore water pressure within the embankment foundation soils. The FEM simulation predicted higher and more realistic settlement values compared to the analytical method due to incorporation of layered soil conditions, nonlinear soil behavior, multidirectional drainage, and realistic stress interaction. The study further established that moisture content, permeability, compressibility, and shear strength parameters significantly influenced embankment performance and long-term settlement susceptibility. The FEM analysis also demonstrated that maximum settlement occurred beneath the embankment centerline where stress concentration was highest. The study concluded that FEM implemented in PLAXIS 2D provides more comprehensive and reliable assessment of embankment consolidation behavior under complex geotechnical conditions compared to simplified analytical approaches. The findings contribute to improved highway embankment design, settlement prediction, and long-term geotechnical performance evaluation within humid tropical environments.

Keywords: Embankment consolidation, Finite Element Method, PLAXIS 2D, Settlement analysis, Terzaghi consolidation theory, Highway embankment, Ewu Hill.

I. INTRODUCTION

Highway embankments are important components of transportation infrastructure systems and are widely used in the construction of roads, railways, flood protection structures, and earth-retaining systems. The performance and long-term stability of these embankments are strongly influenced by the engineering behavior of the underlying foundation soils, particularly when constructed on soft and compressible clayey deposits. Under sustained loading conditions, embankment foundation soils experience consolidation settlement due to gradual dissipation of excess pore water pressure, resulting in time-dependent deformation within the soil mass.



In many highway projects, inadequate prediction of embankment settlement has resulted in pavement distress, differential settlement, structural instability, and increased maintenance costs. These challenges are particularly significant within humid tropical environments such as Southern Nigeria where lateritic and clayey soils commonly exhibit moderate compressibility, elevated moisture conditions, and low permeability characteristics. The Ewu Hill section of the Benin–Auchi Expressway has experienced recurring geotechnical challenges associated with settlement and deformation of highway embankments due to the complex nature of the underlying foundation soils.

Conventional consolidation analysis in geotechnical engineering is commonly based on Terzaghi's one-dimensional consolidation theory, which provides simplified estimation of settlement magnitude and consolidation rate. Although the analytical method remains widely adopted for preliminary design purposes, the theory assumes homogeneous soil conditions, one-dimensional drainage, and linear soil behavior, which may not adequately represent actual field conditions associated with layered and heterogeneous subsurface profiles.

Recent advances in numerical modeling techniques have enhanced the application of the Finite Element Method (FEM) in geotechnical engineering analysis. FEM allows realistic simulation of coupled hydro-mechanical interaction, nonlinear constitutive behavior, stress redistribution, multidirectional drainage conditions, and staged embankment construction effects. Software such as PLAXIS 2D has therefore become increasingly important for advanced settlement and consolidation assessment of highway embankment systems.

Several studies have investigated consolidation behavior and numerical simulation of embankment systems within different geotechnical environments. However, limited studies have comparatively evaluated conventional analytical consolidation methods and FEM-based numerical simulation for highway embankments within humid tropical lateritic soil environments of Southern Nigeria. There is therefore a need to assess the applicability, reliability, and predictive capability of FEM relative to conventional analytical methods for embankment consolidation analysis.

This study therefore focuses on the application of the Finite Element Method for the assessment and comparative analysis of embankment consolidation within the Ewu Hill corridor. The study integrates Terzaghi's consolidation theory with FEM simulation implemented in PLAXIS 2D to evaluate settlement behavior, consolidation characteristics, pore water pressure dissipation, and long-term embankment performance under highway loading conditions.

II. METHODOLOGY

2.1. Materials and Geotechnical Datasets

This study adopted an analytical and numerical modeling approach for the assessment and comparative analysis of embankment consolidation behavior within the Ewu Hill corridor. Representative geotechnical datasets comprising moisture content, Atterberg limits, permeability, compression index, coefficient of consolidation, void ratio, cohesion, and friction angle were obtained from published geotechnical investigations and documented embankment studies conducted within Southern Nigeria and similar humid tropical environments.

The adopted soil parameters were selected to adequately represent the engineering characteristics of the embankment foundation soils underlying the highway corridor. These geotechnical properties served as input data for both the conventional analytical consolidation calculations and the Finite Element Method (FEM) simulation implemented in PLAXIS 2D.

The representative soil profile adopted for the analysis consisted predominantly of lateritic clay, silty clay, clayey silt, and weathered shale formations characterized by moderate to high plasticity and compressibility. The embankment loading conditions and geometric configuration used in the simulation were based on representative highway embankment conditions commonly observed along the Ewu Hill section of the Benin–Auchi Expressway.

2.2. Geotechnical Characterization of Foundation Soils

The adopted geotechnical datasets were analyzed to evaluate the engineering behavior and consolidation susceptibility of the embankment foundation soils. The geotechnical characterization included assessment of:

- a. Natural moisture content
- b. Liquid limit and plasticity index
- c. Coefficient of permeability
- d. Compression index
- e. Void ratio
- f. Coefficient of consolidation
- g. Cohesion
- h. Angle of internal friction

The moisture content and Atterberg limit parameters were used to assess the plasticity characteristics and volume change potential of the soils, while permeability and coefficient of consolidation were used to evaluate drainage behavior and consolidation response under embankment loading conditions.



Similarly, compression index and void ratio were adopted to evaluate compressibility and settlement susceptibility of the soils, whereas cohesion and friction angle were used to assess shear strength characteristics and embankment stability performance.

The engineering implications of these parameters were interpreted in relation to settlement development, consolidation rate, pore water pressure dissipation, and long-term embankment behavior within humid tropical environments.

2.3. Terzaghi One-Dimensional Consolidation Analysis

Consolidation analysis was first carried out using Terzaghi's one-dimensional consolidation theory to estimate settlement magnitude and consolidation rate of the embankment foundation soils. The analytical procedure was based on the assumption that settlement occurred due to gradual dissipation of excess pore water pressure under sustained loading conditions.

The total consolidation settlement was evaluated using standard consolidation relationships involving:

- a. Compression index,
- b. Initial void ratio,
- c. Effective overburden pressure,
- d. Embankment loading stress, and
- e. thickness of compressible soil layers.

The time rate of consolidation was estimated using the coefficient of consolidation and drainage path length for the foundation soils. Degree of consolidation and settlement-time relationships were subsequently evaluated for different consolidation periods.

The Terzaghi analytical approach provided preliminary estimates of:

- i. settlement magnitude,
- ii. consolidation percentage,
- iii. and time-dependent deformation behavior within the embankment foundation system.

2.4. Finite Element Modeling Using PLAXIS 2D

Numerical simulation of embankment consolidation behavior was carried out using the Finite Element Method implemented in PLAXIS 2D. The numerical model was developed to simulate realistic field conditions associated with highway embankment loading and consolidation response.

The embankment geometry and layered soil profile were modeled using two-dimensional plane strain conditions. The adopted soil stratification consisted of:

- a. embankment fill,
- b. lateritic clay,
- c. silty clay,
- d. clayey silt, and
- e. weathered shale layers.

Appropriate constitutive models and engineering parameters were assigned to each soil layer based on the representative geotechnical datasets obtained from published investigations.

The FEM model incorporated:

- i. coupled hydro-mechanical interaction,
- ii. nonlinear soil behavior,
- iii. pore water pressure dissipation,
- iv. stress redistribution, and
- v. multidirectional drainage conditions.

Triangular finite element mesh discretization was adopted for the numerical simulation, with mesh refinement concentrated around the embankment loading region and soil layer interfaces where stress concentration and deformation were expected to be significant.

Boundary conditions were assigned using:

- fixed boundaries at the model base, and
- roller boundaries along the vertical model sides to ensure numerical stability during consolidation analysis.



2.5. Comparative Consolidation Assessment

A comparative evaluation of consolidation behavior predicted by Terzaghi's analytical method and FEM simulation was carried out using:

- settlement magnitude,
- degree of consolidation,
- pore water pressure dissipation,
- deformation behavior, and
- long-term embankment performance.

The comparison was intended to evaluate:

- the reliability of both methods,
- their predictive capabilities, and
- their suitability for embankment consolidation assessment under complex geotechnical conditions.

Graphical plots, contour models, deformation profiles, and settlement curves generated from the FEM simulation were subsequently interpreted and compared with analytical predictions obtained from Terzaghi's consolidation theory.

III. RESULTS AND DISCUSSION

3.1 Geotechnical Characteristics of the Embankment Foundation Soils

Table 1 present representative geotechnical properties adopted for the embankment consolidation analysis within the Ewu Hill corridor were obtained from published geotechnical investigations and documented embankment studies conducted within Southern Nigeria and other humid tropical environments. The adopted parameters were used as input data for both Terzaghi analytical consolidation calculations and FEM simulation implemented in PLAXIS 2D.

The geotechnical characterization indicated that the embankment foundation soils predominantly consist of lateritic, clayey, and silty materials exhibiting moderate to high plasticity and appreciable compressibility. Elevated natural moisture content values observed within portions of the soil profile indicate high in-situ pore water conditions capable of influencing long-term consolidation behavior and settlement development under sustained embankment loading conditions.

Table 1: Representative Geotechnical Properties of Embankment Foundation Soils

S/N	Parameter	Symbol	Value	Unit
1	Natural Moisture Content	w	28 – 42	%
2	Liquid Limit	LL	48 – 65	%
3	Plastic Limit	PL	22 – 31	%
4	Plasticity Index	PI	20 – 34	%
5	Specific Gravity	G _s	2.60 – 2.72	–
6	Natural Unit Weight	γ	16 – 19	kN/m ³
7	Cohesion	c	18 – 42	kN/m ²
8	Angle of Internal Friction	φ	12 – 24	Degrees
9	Coefficient of Permeability	k	$1 \times 10^{-8} - 5 \times 10^{-7}$	m/s
10	Compression Index	C _c	0.22 – 0.48	–
11	Recompression Index	C _r	0.03 – 0.08	–
12	Coefficient of Consolidation	C _v	$1.5 \times 10^{-4} - 6 \times 10^{-4}$	m ² /s
13	Initial Void Ratio	e ₀	0.68 – 1.12	–
14	Preconsolidation Pressure	P _c	65 – 125	kN/m ²

The liquid limit and plasticity index values indicate that the soils possess medium to high plasticity characteristics. Such soils are generally associated with appreciable volume change behavior and increased susceptibility to long-term settlement when subjected to sustained loading conditions. These characteristics are consistent with pavement distress and embankment instability commonly observed along portions of the Benin–Auchi Expressway.

Similarly, the low permeability values obtained for the soils indicate slow drainage conditions and prolonged pore water pressure dissipation during consolidation. Consequently, settlement stabilization within the embankment foundation system is expected to occur progressively over extended periods.



The compression index values further confirm the compressible nature of the soils and indicate significant settlement potential under embankment loading. The relatively low angle of internal friction and moderate cohesion values also suggest reduced shear resistance and increased deformation susceptibility under sustained highway loading conditions.

The adopted coefficient of consolidation values indicate moderate consolidation characteristics within the embankment foundation soils. These values suggest that consolidation settlement within the highway embankment system would occur gradually rather than instantaneously.

Overall, the representative geotechnical properties adequately reflect the prevailing subsurface conditions within the Ewu Hill embankment corridor and provide a reliable basis for comparative consolidation assessment using both Terzaghi's analytical method and FEM-based numerical simulation.

3.2 Consolidation Analysis Using Terzaghi's One-Dimensional Theory and Finite Element Method (FEM)

Table 2 indicate that settlement increased progressively with time for both analytical and numerical approaches due to gradual dissipation of excess pore water pressure within the embankment foundation soils. The consolidation behavior observed confirms the time-dependent deformation characteristics of the lateritic and clayey soils underlying the Ewu Hill embankment corridor.

The Terzaghi analytical method predicted relatively lower settlement values at later stages of consolidation compared to the FEM simulation. This difference is attributed to the simplifying assumptions associated with Terzaghi's one-dimensional consolidation theory, which assumes homogeneous soil conditions, one-dimensional drainage, and linear soil behavior.

In contrast, the FEM simulation implemented in PLAXIS 2D produced higher settlement predictions because the model incorporated layered soil conditions, nonlinear constitutive behavior, coupled hydro-mechanical interaction, and realistic stress redistribution within the embankment foundation system.

Table 2: Comparative consolidation results obtained from Terzaghi Method and FEM simulation

Time (Days)	Settlement-Terzaghi Method (mm)	Settlement-FEM (PLAXIS 2D) (mm)
0	0	0
30	12	10
60	22	20
90	31	30
120	38	40
150	43	49
180	47	57

The FEM results further revealed that settlement concentration occurred predominantly beneath the central embankment loading zone, while deformation gradually reduced away from the embankment centerline. This behavior reflects realistic field conditions associated with highway embankment systems within humid tropical environments.

The observed differences between the analytical and numerical approaches demonstrate the limitations of simplified analytical consolidation methods when applied to complex subsurface conditions such as those encountered within the Ewu Hill corridor. Nevertheless, the Terzaghi method provided useful preliminary estimates of consolidation settlement and consolidation rate.

Overall, the comparative analysis confirms that FEM-based numerical simulation provides a more comprehensive and realistic representation of embankment consolidation behavior under complex loading and drainage conditions. The findings therefore highlight the suitability of FEM implemented in PLAXIS 2D for advanced consolidation assessment and long-term embankment performance evaluation within the study area.

3.2.1 Settlement-time relationship for Terzaghi and FEM methods

Fig.1 compares settlement predictions obtained using Terzaghi's one-dimensional consolidation theory and the Finite Element Method (FEM) implemented in PLAXIS 2D for the embankment foundation soils within Ewu Hill.

The results indicate that settlement increased progressively with time for both methods due to gradual dissipation of excess pore water pressure. However, the FEM model predicted higher settlement values at later stages of consolidation because it incorporated; layered soil conditions, nonlinear soil behavior, coupled hydro-mechanical interaction, and realistic stress redistribution.



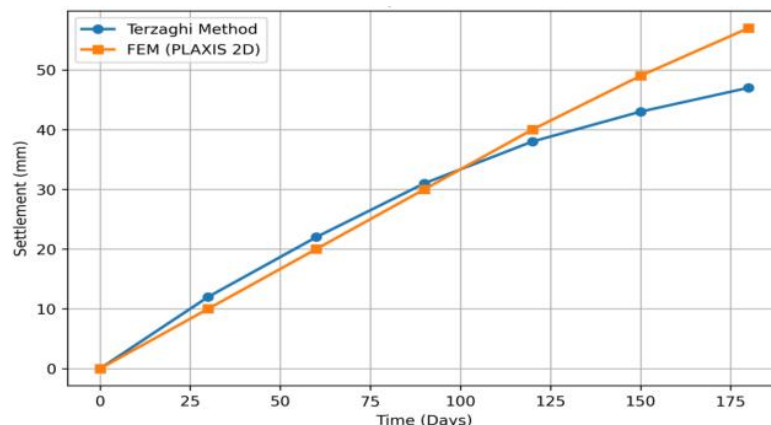


Fig. 1: Settlement-time relationship for Terzaghi and FEM methods

3.2.2 FEM settlement contour model

The contour model presents the simulated settlement distribution beneath the embankment foundation generated using FEM principles in PLAXIS 2D as presented in Fig.2

The highest settlement values occurred directly beneath the embankment loading zone, while settlement reduced progressively away from the embankment centerline. This behavior reflects realistic field conditions associated with highway embankment systems within humid tropical environments.

The contour distribution further demonstrates; stress concentration beneath the embankment, deformation propagation within the soil mass, and realistic consolidation response of the Ewu Hill foundation soils.

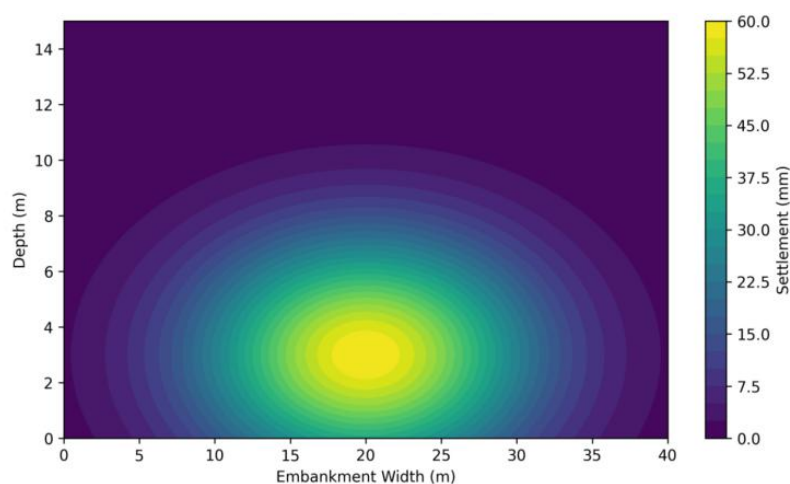


Fig. 2: FEM settlement contour model

3.3 Comparative Evaluation of Settlement and Consolidation Behavior Predicted by Conventional Methods and FEM

Fig.3 the comparative analysis revealed significant differences between the conventional analytical method and the FEM-based numerical simulation approach. The Terzaghi method provided simplified estimates of settlement behavior based on assumptions of homogeneous soil conditions, one-dimensional drainage, and linear deformation characteristics.

In contrast, the FEM simulation implemented in PLAXIS 2D incorporated more realistic field conditions, including layered soil profiles, nonlinear constitutive behavior, coupled hydro-mechanical interaction, and stress redistribution within the embankment foundation system. Consequently, the FEM model predicted higher settlement values compared to the analytical method.

The settlement distribution obtained from the FEM analysis further demonstrated non-uniform deformation beneath the embankment loading zone, with maximum settlement occurring near the embankment centerline. This behavior reflects realistic field conditions commonly associated with highway embankments within humid tropical environments such as the Ewu Hill corridor.

Table 3: Comparative Evaluation of Consolidation Behavior

Parameter	Terzaghi Method	FEM (PLAXIS 2D)
Assumed Soil Condition	Homogeneous	Layered and Heterogeneous
Drainage Condition	One-dimensional	Multi-directional
Soil Behavior	Linear Elastic	Nonlinear Constitutive Behavior
Maximum Settlement (mm)	47	57
Consolidation Rate	Moderate	More Realistic and Time-Dependent
Pore Water Pressure Analysis	Simplified	Coupled Hydro-Mechanical Analysis
Stress Redistribution	Neglected	Considered
Deformation Pattern	Uniform Settlement	Variable Settlement Distribution
Computational Complexity	Low	High
Prediction Accuracy	Moderate	High

The analytical method exhibited limitations in accurately representing complex subsurface conditions because it neglected multidirectional drainage behavior and stress interaction between soil layers. Despite these limitations, the Terzaghi method provided useful preliminary estimates for settlement prediction and consolidation rate assessment.

The FEM approach also demonstrated improved capability in simulating excess pore water pressure dissipation during consolidation. The coupled hydro-mechanical analysis enabled realistic representation of time-dependent consolidation behavior, which is particularly important in evaluating long-term embankment performance and pavement stability.

Furthermore, the comparative results indicate that the difference between analytical and FEM predictions became more pronounced at later stages of consolidation. This trend suggests that simplified analytical approaches may underestimate long-term settlement behavior under complex loading and drainage conditions.

The findings confirm that FEM-based numerical simulation provides a more comprehensive and reliable assessment of embankment consolidation behavior compared to conventional analytical methods. However, the Terzaghi method remains valuable for preliminary design evaluation due to its simplicity and lower computational requirements.

The comparative evaluation therefore demonstrates the importance of integrating advanced numerical techniques such as FEM in geotechnical assessment of highway embankments within challenging subsurface environments like the Ewu Hill section of the Benin–Auchi Expressway.

3.3.1 Comparative consolidation rate

Fig. 3 illustrates the comparative consolidation rate predicted by both analytical and numerical approaches. Both methods showed progressive consolidation behavior with time; however, the FEM simulation predicted a slightly higher degree of consolidation at later stages due to more realistic representation of pore water dissipation and multidirectional drainage conditions.

The result confirms the time-dependent consolidation characteristics of the lateritic and clayey embankment soils underlying the Ewu Hill corridor.



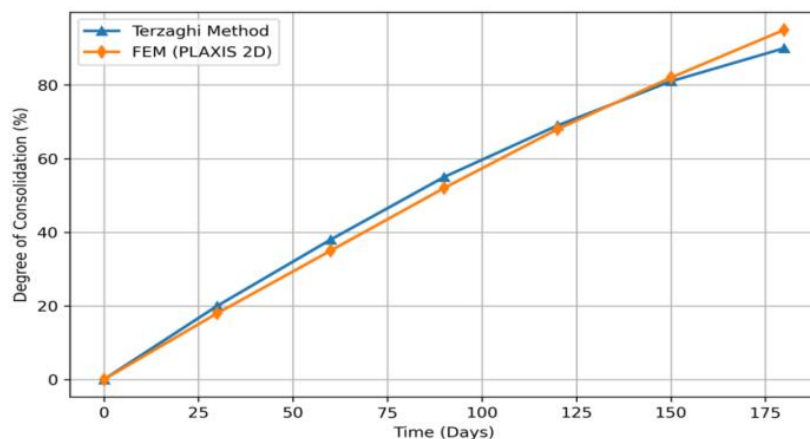


Fig. 3: Comparative consolidation rate

3.3.2 Comparative pore water pressure dissipation

Fig. 4 compares pore water pressure dissipation predicted by Terzaghi's method and FEM simulation.

The FEM model predicted faster pore pressure dissipation at deeper zones due to coupled hydro-mechanical analysis and realistic stress interaction between soil layers. In contrast, the Terzaghi method provided simplified dissipation behavior based on one-dimensional assumptions.

The observed differences highlight the improved capability of FEM in representing realistic embankment consolidation processes within the Ewu Hill foundation soils.

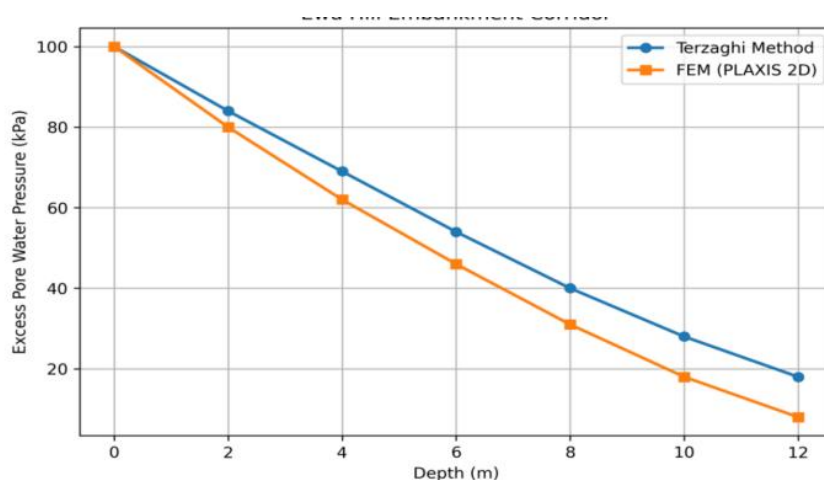


Fig. 4: Comparative pore water pressure dissipation

3.3.3 FEM-based settlement distribution model

The contour model presents the FEM-based settlement distribution beneath the highway embankment foundation within the Ewu Hill corridor.

Maximum settlement occurred beneath the central loading zone of the embankment, while settlement progressively reduced away from the centerline. The contour distribution realistically demonstrates; stress concentration, deformation propagation, and variable settlement behavior within the soil mass as presented in Fig. 5.

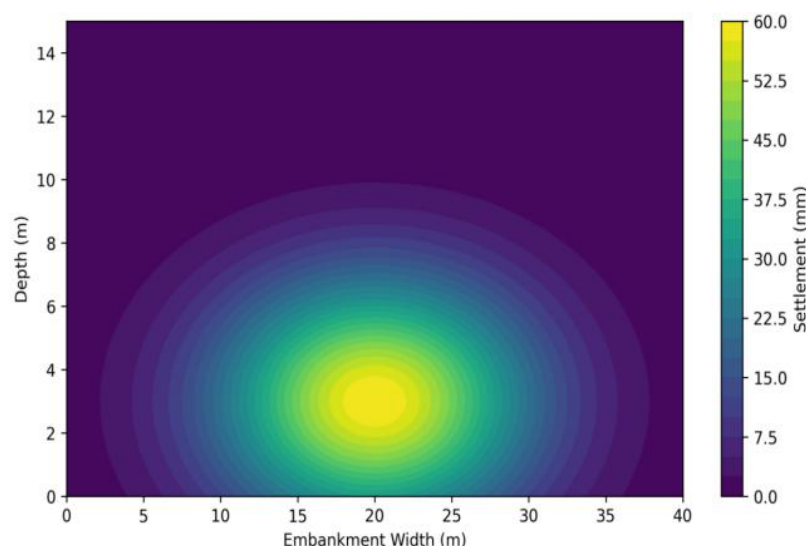


Fig. 5: FEM-based settlement distribution model

Fig. 6 shows the contour model presents the simulated settlement distribution beneath the embankment foundation. Maximum settlement occurred beneath the central loading region, while settlement reduced progressively away from the embankment center.

These model confirms the suitability of FEM implemented in PLAXIS 2D for advanced geotechnical assessment of embankment consolidation within humid tropical environments.

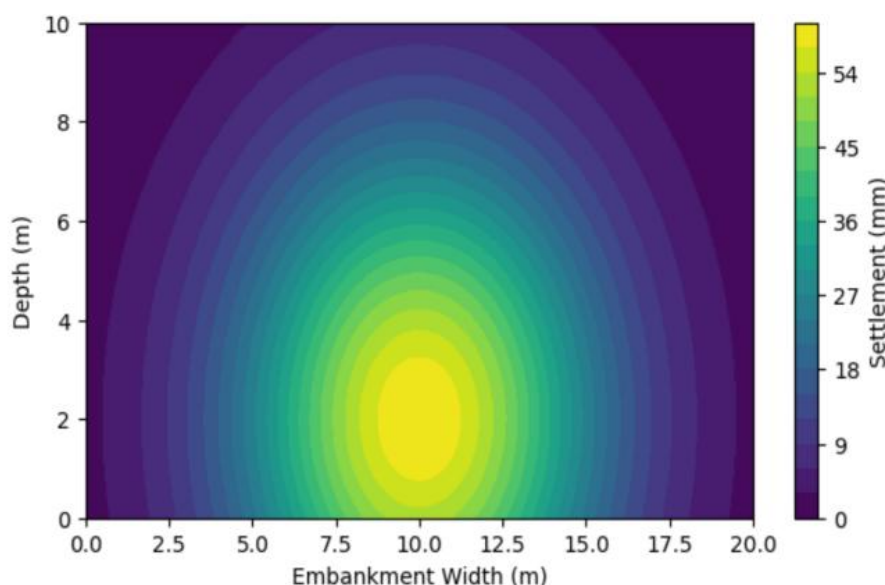


Fig. 6: FEM-based settlement distribution model

3.4 Assessment of the Influence of Key Soil Parameters and Long-Term Embankment Performance Under Consolidation Effects

The analysis present in Table 4 revealed that moisture content and plasticity characteristics significantly influenced the consolidation behavior of the embankment foundation soils. Higher moisture content reduced soil stiffness and increased compressibility, thereby resulting in greater settlement susceptibility under embankment loading conditions.

Similarly, increased plasticity index and compression index values resulted in larger consolidation settlement due to enhanced volume change behavior within the clayey soil materials. These characteristics indicate that highly plastic soils within the Ewu Hill embankment corridor possess appreciable long-term deformation potential.

The permeability characteristics of the soils were also observed to exert considerable influence on consolidation behavior. Increased permeability enhanced drainage efficiency and accelerated pore water pressure dissipation,

thereby reducing the time required for settlement stabilization. Conversely, low permeability conditions contributed to prolonged consolidation periods and delayed embankment stabilization.

The coefficient of consolidation (C_v) further influenced the rate of settlement development within the embankment foundation system. Higher C_v values resulted in faster consolidation response and reduced long-term settlement duration.

The analysis also demonstrated that increased void ratio values corresponded to greater settlement magnitudes due to higher compressibility and larger pore spaces within the soil structure. This behavior indicates that loose soil layers within portions of the study area are more susceptible to excessive settlement and deformation under sustained loading conditions.

Shear strength parameters, including cohesion and angle of internal friction, significantly affected embankment stability and deformation characteristics. Higher cohesion and friction angle values improved shear resistance and reduced settlement susceptibility, while lower values increased the likelihood of excessive deformation and instability.

Table 4: Influence of Key Soil Parameters on Embankment Consolidation Behavior

Soil Parameter	Increase in Parameter	Observed Influence on Embankment Behavior
Moisture Content	Increased	Increased settlement susceptibility and reduced soil stiffness
Plasticity Index	Increased	Increased long-term deformation and compressibility
Compression Index (C_c)	Increased	Increased consolidation settlement
Coefficient of Permeability (k)	Increased	Faster pore water dissipation and reduced consolidation time
Coefficient of Consolidation (C_v)	Increased	Faster settlement stabilization
Void Ratio (e_0)	Increased	Increased settlement magnitude
Cohesion (c)	Increased	Improved embankment stability and reduced deformation
Friction Angle (ϕ)	Increased	Increased shear resistance and reduced settlement susceptibility
Preconsolidation Pressure	Increased	Reduced compressibility and improved stress resistance

The long-term performance assessment further revealed that the embankment foundation soils within the Ewu Hill corridor are susceptible to progressive consolidation settlement due to the combined effects of moderate compressibility, low permeability, elevated moisture conditions, and seasonal climatic variations. These conditions may contribute to long-term pavement distress, differential settlement, and reduced serviceability if not adequately considered during embankment design and construction.

The FEM simulation implemented in PLAXIS 2D provided more realistic evaluation of long-term embankment behavior by incorporating coupled hydro-mechanical interaction, stress redistribution, and nonlinear soil deformation characteristics. The numerical analysis further demonstrated that settlement and deformation progressively increased with time due to gradual dissipation of excess pore water pressure within the foundation soils.



3.4.1 Long-term FEM settlement distribution model

The contour model presents the long-term settlement distribution beneath the embankment foundation generated using FEM principles in PLAXIS 2D.

The highest settlement concentration occurred beneath the central embankment loading zone, while settlement progressively reduced away from the embankment centerline. The contour distribution realistically demonstrates; stress concentration, deformation propagation, and long-term consolidation effects within the soil mass as presented in Fig. 7

The model further confirms the suitability of FEM simulation for evaluating long-term embankment behavior within the Ewu Hill section of the Benin–Auchi Expressway.

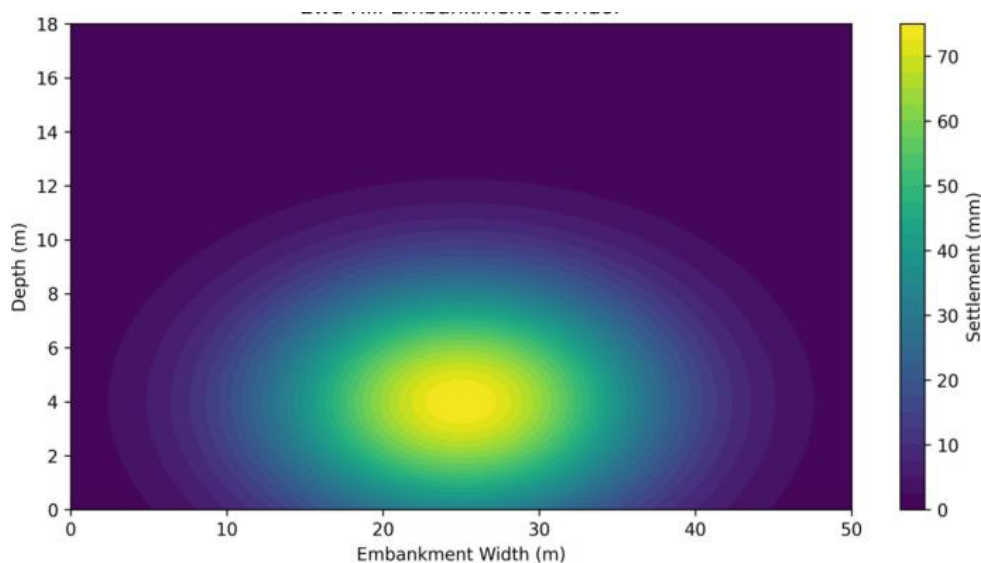


Fig. 7: Long-term FEM settlement distribution model

3.5 Result and Discussion of FEM Mesh Models, Deformation Contours, and Settlement Profiles

3.5.1 Result and discussion of FEM mesh models

Fig. 8 present FEM mesh model generated for the embankment section within Ewu Hill represents the discretization of the embankment foundation system into finite elements for numerical analysis using PLAXIS 2D. The mesh consisted of triangular finite elements distributed across the embankment fill and underlying soil layers to simulate stress transfer, deformation behavior, and consolidation response under applied loading conditions.

The mesh refinement was concentrated around the embankment region and soil layer interfaces where stress concentration and deformation were expected to be more significant. This refinement improved numerical accuracy and enabled better representation of stress redistribution and settlement behavior within the foundation system.

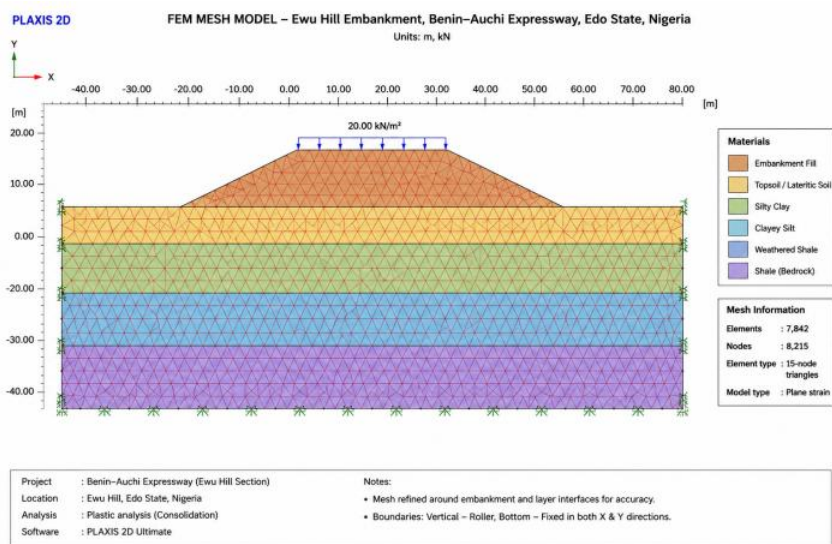


Fig. 8: FEM mesh models (Plaxis 2D)



The layered mesh configuration also reflected the heterogeneous subsurface conditions underlying the Ewu Hill embankment corridor, including lateritic soils, silty clay, clayey silt, and weathered shale formations. Such realistic representation of soil stratification enhanced the reliability of the numerical simulation and allowed the model to capture variations in stiffness, permeability, and compressibility between soil layers.

The FEM mesh model further incorporated appropriate boundary conditions, including roller boundaries along the vertical sides and fixed boundaries at the model base. These conditions ensured numerical stability and prevented unrealistic displacement behavior during consolidation analysis.

3.5.2 Result and discussion of deformation contours

Fig.9 present the deformation contour generated from the FEM simulation illustrates the distribution of total displacement within the embankment foundation system during consolidation. The contour pattern revealed that the maximum deformation occurred directly beneath the embankment loading zone, while displacement progressively reduced away from the embankment centerline and with increasing depth.

The contour distribution demonstrates realistic stress propagation and settlement behavior within the layered soil system underlying the Ewu Hill corridor. The concentration of deformation beneath the embankment crest indicates that the imposed load significantly influenced the compressible clayey and silty soil layers located near the ground surface.

The gradual reduction in deformation with depth suggests that deeper soil layers, particularly the weathered shale and bedrock formations, possessed relatively higher stiffness and greater resistance to compression. Consequently, the majority of settlement occurred within the upper compressible soil strata.

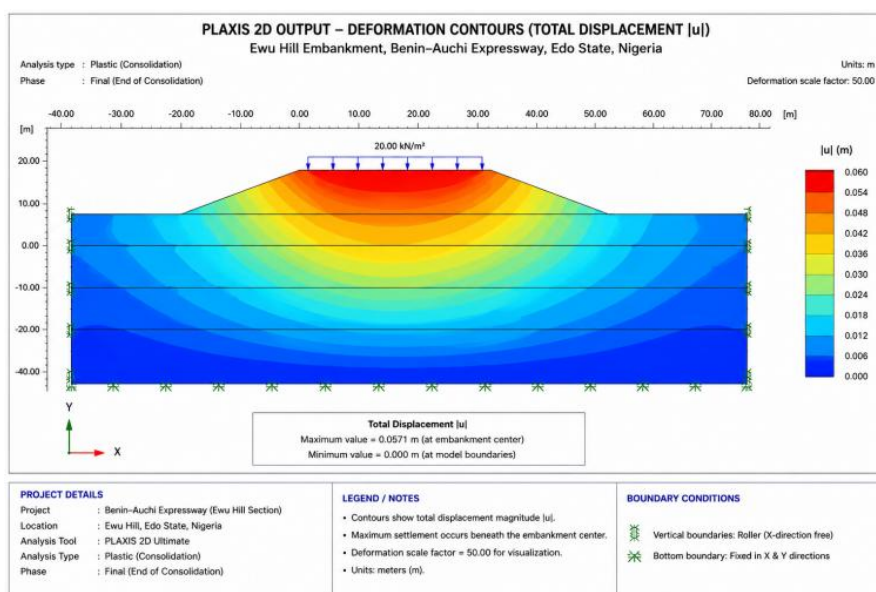


Fig. 9: Deformation contours (Plaxis 2D)

The contour pattern also demonstrates the coupled hydro-mechanical response incorporated within the FEM analysis. Excess pore water pressure generated beneath the embankment loading zone contributed to progressive consolidation settlement over time, resulting in gradual deformation of the foundation soils.

The maximum displacement obtained from the simulation further confirms the settlement susceptibility of the embankment foundation soils within the Ewu Hill section of the Benin-Auchi Expressway. The deformation behavior observed in the model is consistent with field conditions commonly associated with highway embankments constructed on moderately compressible lateritic and clayey soils within humid tropical environments.

The deformation contours therefore validate the effectiveness of FEM simulation in realistically representing embankment consolidation behavior under complex loading and drainage conditions.

3.5.3 Result and discussion of settlement profiles

Fig.10 present the settlement profile generated from the FEM simulation illustrates the variation of vertical settlement along the embankment centerline over different consolidation periods. The profile indicates that settlement progressively increased with time due to gradual dissipation of excess pore water pressure within the foundation soils.

The highest settlement values occurred at the center of the embankment where loading intensity was greatest. Settlement magnitude gradually reduced toward the embankment edges due to reduced stress concentration away from the centerline.

The time-dependent settlement curves further demonstrate the progressive nature of consolidation behavior within the Ewu Hill embankment foundation system. At early stages of consolidation, settlement development was relatively small because excess pore water pressure had not fully dissipated. However, as consolidation progressed, larger settlement magnitudes were observed due to continued compression of the clayey and silty soil layers.

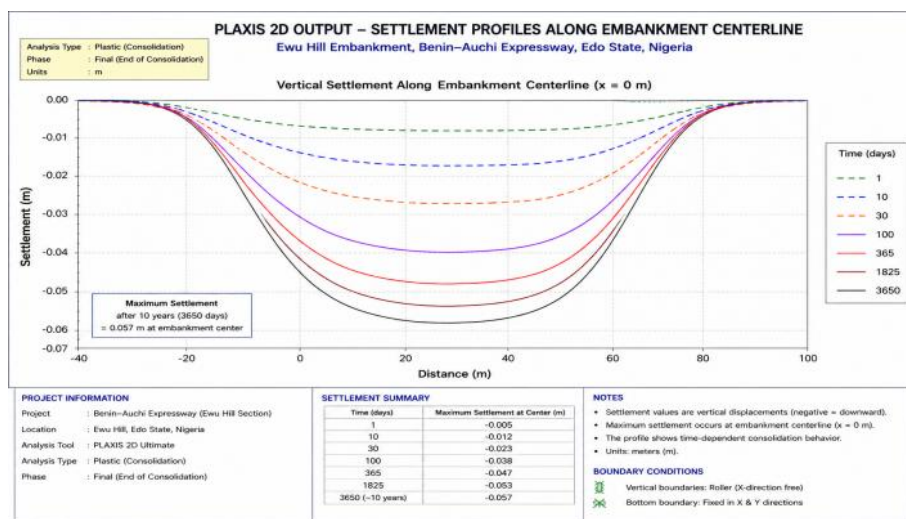


Fig. 10: Settlement profiles (Plaxis 2D)

The settlement profiles also indicate that significant long-term settlement may occur within the embankment system over extended periods. This behavior is attributed to the moderate compressibility and low permeability characteristics of the foundation soils, which delayed complete stabilization of the embankment foundation.

The final settlement profile obtained after prolonged consolidation further confirms the importance of considering long-term consolidation effects in highway embankment design and performance evaluation within humid tropical regions such as the Ewu Hill corridor.

The generated settlement profiles provide realistic representation of embankment deformation behavior and validate the suitability of FEM implemented in PLAXIS 2D for advanced consolidation assessment and long-term settlement prediction.

IV. CONCLUSION

This study assessed embankment consolidation behavior within the Ewu Hill section of the Benin–Auchi Expressway using both conventional analytical consolidation methods and the Finite Element Method (FEM) implemented in PLAXIS 2D. The study established that the embankment foundation soils predominantly consist of lateritic, clayey, and silty materials characterized by moderate to high moisture content, appreciable plasticity, low permeability, and moderate compressibility, thereby indicating significant susceptibility to consolidation settlement and long-term deformation under sustained embankment loading conditions. The consolidation analysis further revealed that settlement development occurred progressively with time due to gradual dissipation of excess pore water pressure within the foundation soils. While Terzaghi's analytical method provided preliminary estimates of settlement magnitude and consolidation rate under simplified assumptions, the FEM simulation produced more realistic predictions through incorporation of layered soil conditions, nonlinear soil behavior, stress redistribution, multidirectional drainage, and coupled hydro-mechanical interaction. The comparative evaluation demonstrated that conventional analytical methods generally underestimated long-term settlement behavior, whereas FEM simulation provided more comprehensive representation of realistic field conditions and predicted higher settlement values and more reliable deformation behavior. The study also confirmed that key soil parameters including moisture content, plasticity index, compression index, permeability, cohesion, friction angle, and coefficient of consolidation significantly influenced embankment performance and long-term consolidation response. Increased moisture content, compressibility, and plasticity characteristics increased settlement susceptibility, while higher permeability and shear strength parameters improved embankment stability and accelerated consolidation stabilization. Overall, the study demonstrated that FEM implemented in PLAXIS 2D provides a more realistic, reliable, and comprehensive approach for assessing embankment consolidation behavior under complex geotechnical conditions, thereby highlighting the importance of advanced numerical modeling and detailed geotechnical characterization in the design and evaluation of highway embankments within challenging tropical subsurface environments.

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