The stability analysis of a highway embankment founded on lime-stabilized soft soils in Calabar, Southeast Nigeria

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Abstract. Highway embankment failures are common phenomena in Southern Nigeria. To this end, in situ geotechnical tests and laboratory analyses were used to characterize the underlying lithologic units along a highway alignment in Calabar, Nigeria. The engineering behaviour of the soils mixed with various lime contents was evaluated after a curing period of 28 days. Limit equilibrium analysis was used to determine the factor of safety (FS) for the most critical slip surface for the embankment with height in the range of 4 to 7 m. Undrained triaxial tests conducted on the unstabilized soil indicate an undrained shear strength of 10 to 17 kPa, while the undrained shear strength of the lime-stabilized soils varied from 87 to 198 kPa, as lime content increased from 3 to 12%. Stability analysis carried out on the unstabilized soil samples indicates that FS ranged from 0.88 to 1.33 for the various embankment heights and analysis methods, while FS for the shallow (1-5 m) stabilization varied from 1.09 to 5.02 for the various embankment heights, lime contents and analysis methods. The stability of the embankment was found to increase with an increase in lime content and depth of stabilization even for the most extreme loading condition.

Keywords: Highway embankment, Stability analysis, Factor of safety, Soft soil foundation

1. Introduction

Expansive soils pose a significant threat to the service life of pavements founded on highway embankments. These engineering problems are common in the Nigerian humid tropical wetlands where the influence of high-intensity rainfalls on soft soil foundations leads to significant volumetric changes due to the variation of the natural moisture content of the soil. These processes cause extensive and differential settlements on the embankment. Furthermore, highway embankments oftentimes undergo small to large-scale deformations during and after construction, giving rise to safety concerns due to shear failures that occur during or immediately after construction [1,2]. Embankments are characteristically designed to satisfy safety and stability requirements measured as the embankment’s factor of safety (FS) against shear failure and magnitude of permissible deformation with respect to displacement.

During the construction of earthworks, quick loading usually occurs in soft soil foundations underlying most embankments due to changes in the prevailing equilibrium stress regimes, which are generated by the weight of the embankment [3]. This ultimately leads to an increase in pore-water pressure, and the dissipation of the excess pore-water pressure generated by the weight of the embankment is generally slow in expansive soils [4,5]. Consequently, undrained loading tends to occur in soft soil foundations due to the inability of the soil to gain strength from the dissipation of the generated excess pore-water pressure as a result of the poor drainage characteristics of expansive soils.
This implies that embankments constructed on soft soil foundations are prone to cumulative increases in pore-water pressures which ultimately lead to internal stress redistribution, differential settlement, and failure [6,7]. Therefore, this research aims to investigate the suitability of using lime to improve the engineering properties of a soft soil foundation and the overall engineering behaviour (stability analysis) of the lime-stabilized soft soil foundation and embankment. The significance of this research lies in the application of the limit equilibrium method for determining the minimum FS required for the long-term performance of highway embankments founded on lime-stabilized soft soil foundations.

2. Materials and Methods

2.1. Location, geology and site condition

A 20 km highway project has been under construction in Calabar, Cross River state, Nigeria. The highway, which is located approximately 20 km north-east of Calabar, originates from Odukpani junction in Odukpani Local Government Area and terminates in Akamkpa Local Government Area, both in Cross River state, Nigeria. Thick deposits of expansive soils constitute the dominant materials underlying many sections of the highway. The study area falls within the humid tropical climate zone of Nigeria with average annual rainfall and temperature of 2750 mm and 26.1°C, respectively. Some sections of the proposed highway alignment are seasonally flooded, and groundwater level varies from 2 to 2.5 m; complete flooding occurs during high-intensity rainfalls, especially in the months of July and September. Geologically, the study area is located in the Calabar Flank sedimentary basin of Nigeria. The stratigraphic sequence of the Calabar Flank ranges from the fluvio-deltaic sandstones of the Awi Formation to the dark-grey carbonaceous Nkporo Shale. The Nkporo Shale, including the Ekenkpon Shale and the New Netim Marl outcrop at the site, and some of these materials have been blasted to create an access road for the highway alignment.

The prospects and cost of constructing the highway have been gravely undermined by engineering problems associated with soft soil foundation failures under repeated traffic loading. Partial and complete failure of some sections of the already constructed highway embankment includes some of the challenges witnessed in the area together with the failure of road culverts along their centerlines (Figure 1a). Remedial works such as topping up the embankment with fill to achieve level grade have also exacerbated the situation (Figure 1b). It becomes necessary to develop a method that would improve the expansive soil to be able to address the critical issue of foundation failure if the highway is to be safely completed.

![Figure 1. (a) Differential settlement and failure of a road culvert at a section of the highway alignment. (b) Shear failure of the embankment due to the overburden (fill) pressure on the soft soil foundation.](image)

2.2. Geotechnical boring, laboratory tests and stability analysis

Three geotechnical boreholes drilled to a maximum depth of 30 m were used to evaluate the underlying lithologic units and the prevailing stress states. The borings were completed according to
BS 5930 together with the description of the core samples [8]. Class 1 samples were obtained using standard Shelby tubes. Selected samples from the unstabilized expansive soil (USS) were subjected to a range of laboratory tests including particle size distribution, Atterberg limits, unconfined compression tests, and unconsolidated undrained triaxial tests. The stabilized soils were prepared by adding various amounts of locally sourced quicklime (CaO) in the range of 3 to 12% by weight of the soil at its natural moisture content and then cured for a period of 28 days. The quicklime contains about 94% pure calcium oxide. The engineering properties of the lime-stabilized soil samples were evaluated by carrying out a range of laboratory tests including unconfined compression test. Mass stabilization method proposed by Euro SoilStab was adopted for this research [9]. The method involves in situ introduction and mixing of the soil-lime mixtures using specialized mixers, which have the capacity to achieve a 5 m maximum depth of stabilization. Stability analysis using the Bishop’s and Morgenstern-Price methods was carried out to determine the factor of safety (FS) for the critical slip surface by utilizing the optimization process of the GeoStructural Analysis (GSA) software - slope stability submodel (version 18.4). The analysis was done considering the effect of different embankment heights, which ranges from 4 to 7 m for the unstabilized soil and the lime-stabilized soil.

3. Results and Discussion

3.1. Geotechnical analysis of the fill and soft soil foundation

The results of laboratory tests conducted on the natural (unstabilized) soil are summarized in Table 1. Combined analyses of the geotechnical borehole data and the laboratory results indicate that the topsoil (0-7m) underlying the embankment has low to medium plasticity values with fines and sand contents that range from 25 to 45% and 55 to 75%, respectively. The natural moisture content of the soil varies from 19.2 to 24.9%, with liquid limit (LL), plastic limit (PL) and plasticity index (PI) varying from 43 to 58%, 22 to 27% and 21 to 26%, respectively. The basal layer (8-27 m) is dominated by a soft to stiff clayey silt of medium to high plasticity. The material has moisture content that varies from 49.2% to 108.6%, while the LL, PL, and PI range from 63 to 149%, 33 to 75% and 30 to 74%, respectively. The results show that the undrained shear strength (S_u) of the soil varies from 10 to 17 kPa. The fill is classified as clayey sand (SC) according to the Unified Soil Classification System (USCS), while the soft soil foundation is designated as silt of high plasticity (MH). Similarly, the fill is classified as A-2-5, while the soft soil foundation is classified as A-7-5 according to the AASHTO soil classification system, which corresponds to a fair and poor subgrade material, respectively.

| Results                                      | Fill          | Soft Soil Foundation |
|----------------------------------------------|---------------|----------------------|
| | Range  | Average | Range | Average |
| Unit weight (kN/m³) Bulk                    | 19.8-20.6     | 20      | 13.8-16.4 | 15      |
| Moisture content (%) Dry                    | 16.5-16.6     | 17      | 6.8-11    | 8       |
| Liquid Limit (%)                            | 19.2-24.9     | 22.1    | 49.2-108.6 | 86.4   |
| Plastic Limits (%)                          | 43-58         | 51      | 63-149    | 109     |
| Plasticity Index (%)                        | 22-27         | 25      | 33-75     | 56      |
| Plasticity Index (%)                        | 21-26         | 24      | 30-74     | 53      |
| Grain size (%)                              | 55-75         | 5-13    |
| Sand                                         | 25-45         | 87-95   |
| Fine (silt/clay)                            | 25-45         | 87-95   |
| Undrained shear strength (S_u) kPa          | 34-66         | 50      | 10-17     | 15      |
| Friction Angle (°)                          | 7-10          | 9       | 1-3       | 3       |
| USCS                                         | S-CL          | MH      |
| ASSHTO                                       | A-7-5         | A-7-5   |
3.2. Unconfined compressive strength

Figure 2 shows the stress-strain curves of the soft soil foundation treated with various proportions of lime, while Figure 3 shows the results obtained from unconfined compression tests carried out on the soft soil foundation treated with various proportions of lime and cured for a period of 28 days. The result shows that the compressive strength of the stabilized soils increased with an increase in lime content. The increment was in the order: 10, 97, 144, 165, and 198 kPa for lime contents of 0, 3, 6, 10 and 12%, respectively. The result further shows that the compressive strength values of the 0 and 12% lime contents revealed a 1880% increase in strength. The increase in compressive strength of the various soil-lime mixtures could be ascribed to the cation-exchange processes between the clay minerals and lime that led to the formation of cementitious compounds such as calcium-silicate-hydrates (CSH) and calcium-aluminate-hydrates (CAH) [10]. It should be noted that the field strength of chemically stabilized soil is significantly lower than those obtained from laboratory test [9].

![Figure 2](image1.png)  
**Figure 2.** Stress-strain curves of lime-stabilized soft soil foundations after a curing period of 28 days.

![Figure 3](image2.png)  
**Figure 3.** Effect of lime on compressive strength of lime-stabilized soft soil foundation. (Note: LSS = lime stabilized soil).

3.3. Stability analysis

Stability analysis was conducted on the unstabilized soil (USS) using the GeoStructural Analysis (GSA) software - slope stability submodel (version 18.4). Furthermore, the analysis utilized a 1V:2H embankment with height that ranges from 4 to 7 m (Figure 4) and traffic surcharge load of 20 kPa applied on top of the embankment (Figure 5a). Mass stabilization of the top 1~5 m of the soft soil foundation was analyzed for an embankment constructed over the lime-stabilized soil (LSS) having an improved shear strength parameters (Figure 5b) [9]. The short-term stability of the embankment was expected to satisfy a safety factor of 1.3 to be regarded as safe and 1.5 on a long-term basis [11,12].

Results obtained from the stability analysis using the Bishop’s method show that the FS of a 4 m embankment constructed on the unstabilized (natural) soil was 1.2. However, this value decreased with an increase in height of the embankment from 1.2 to 0.88 for an embankment with heights of 4 and 7 m, respectively. The FS values determined from the analysis indicate that the short and long-term stability of the highway embankment constructed over the unstabilized soft soil foundation was below the required safety standards and could be subject to progressive failure over time. However, treating the top 1 m of the soft soil foundation with 3% lime indicated a 33% increase in stability of the 4 m embankment (Figure 6). The results show that FS increased with an increase in the depth of stabilization, indicating that there is a linear relationship between the stability of the highway embankment and depth of stabilization of the foundation. Similar results were obtained for various embankment heights analyzed using the Morgenstern-Price method (Table 2). The overall trend of the
results gives an indication that the major factor influencing the stability of embankments constructed on lime-stabilized soft soil foundations is the stabilization depth (thickness of the stabilized subsoil), compared to the amount of lime used to improve the engineering properties of the soil. The results further show that an extreme case of loading the natural soft soil foundation with a 7 m-high embankment yields a safety factor of 0.88, which indicates a 68% \((FS, 1.48)\) improvement when treated with lime content of 3% to a depth of 3 m (Figure 7). However, this \(FS\) value does not satisfy the long-term stability requirements of the embankment. Consequently, an improvement of 122% was obtained with 10% lime content at a maximum depth of 3 m for an extreme case of loading the foundation with a 7 m-high embankment. The result indicates that treating the soft soil foundation with 10% lime by weight of the natural soil and stabilizing to a maximum depth of 3 m for an extreme case of loading (7 m-high embankment) would improve the overall performance of the highway embankment.

![Figure 4. Cross-section of proposed embankment.](image)

![Figure 5. Embankment and foundation profiles of the: (a) Unstabilized soil; and (b) Soft soil foundation stabilized with lime to depths ranging from 1 to 5 m. (USS = unstabilized soil; LSS = lime-stabilized soil).](image)
**Figure 6.** Factor of safety vs. stabilization depth obtained using the Bishop’s method for a 4 m embankment.

**Figure 7.** Factor of safety vs. stabilization depth obtained using the Bishop’s method for a 7 m embankment.

**Table 2:** Summary of $FS$ determined for various heights of highway embankment

| Stabilization depth (m) | $FS$ - Bishop’s Method | $FS$ - Morgenstern-Price Method |
|------------------------|------------------------|---------------------------------|
|                        | Embankment Height (m)  | Embankment Height (m)           |
|                        | 4          | 5           | 6   | 7   | 4       | 5           | 6   | 7   |
| USS                    |            |             |     |     |         |             |     |     |
| 3%-LSS                 |            |             |     |     |         |             |     |     |
| 1                      | 1.60       | 1.39        | 1.18| 1.09| 1.69    | 1.42        | 1.25| 1.13|
| 2                      | 1.95       | 1.64        | 1.41| 1.27| 1.99    | 1.70        | 1.47| 1.31|
| 3                      | 2.32       | 1.93        | 1.65| 1.48| 2.33    | 1.96        | 1.69| 1.52|
| 4                      | 2.68       | 2.24        | 1.92| 1.68| 2.67    | 2.25        | 1.94| 1.70|
| 5                      | 3.04       | 2.55        | 2.18| 1.92| 3.03    | 2.55        | 2.18| 1.93|
| 6%-LSS                 |            |             |     |     |         |             |     |     |
| 1                      | 1.74       | 1.47        | 1.27| 1.2  | 1.81    | 1.55        | 1.34| 1.21|
| 2                      | 2.29       | 1.92        | 1.63| 1.48| 2.31    | 1.97        | 1.7  | 1.49|
| 3                      | 2.86       | 2.35        | 2.01| 1.81| 2.85    | 2.38        | 2.07| 1.82|
| 4                      | 3.38       | 2.83        | 2.42| 2.14| 3.37    | 2.81        | 2.42| 2.11|
| 5                      | 3.97       | 3.31        | 2.82| 2.49| 3.94    | 3.3         | 2.81| 2.47|
| 10%-LSS                |            |             |     |     |         |             |     |     |
| 1                      | 1.8        | 1.51        | 1.31| 1.18| 1.87    | 1.57        | 1.38| 1.24|
| 2                      | 2.41       | 2.01        | 1.73| 1.57| 2.45    | 2.08        | 1.78| 1.57|
| 3                      | 3.05       | 2.54        | 2.16| 1.95| 3.08    | 2.54        | 2.18| 1.96|
| 4                      | 3.7        | 3.09        | 2.64| 2.34| 3.69    | 3.06        | 2.64| 2.3 |
| 5                      | 4.7        | 3.65        | 3.11| 2.74| 4.35    | 3.62        | 3.08| 2.72|
| 12%-LSS                |            |             |     |     |         |             |     |     |
| 1                      | 1.90       | 1.59        | 1.38| 1.24| 1.96    | 1.65        | 1.44| 1.29|
| 2                      | 2.64       | 2.19        | 1.89| 1.71| 2.68    | 2.27        | 1.93| 1.69|
| 3                      | 3.42       | 2.83        | 2.41| 2.18| 3.44    | 2.82        | 2.42| 2.18|
| 4                      | 4.20       | 3.46        | 2.99| 2.65| 4.18    | 3.46        | 2.98| 2.58|
| 5                      | 5.02       | 4.17        | 3.55| 3.13| 4.99    | 4.14        | 3.53| 3.12|
4. Conclusions
This study investigated the underlying factors affecting the long-term stability and performance of highway embankments founded on soft soil foundations. The safe completion of the 20-km highway project was affected by shear failures and small to large-scale deformations that occur as a result of volumetric changes triggered by variations in the natural moisture content of the soft soil foundation. A combination of geotechnical boreholes drilled to a depth of 30 m and laboratory tests were used to characterize the dominant lithologic units underlying some sections of the highway alignment. The result showed that the plasticity index and the natural moisture content of the soft soil foundation ranged from 30 to 74% and 49.2 to 108.6%, respectively. These poor physical properties, together with the high amount of fines and low undrained shear strength of the soil, which ranged from 10 to 17 kPa, all contributed to the diverse engineering problems encountered in the study area. To overcome these challenges, the present study adopted chemical stabilization of the top 5 m of the soft soil foundation using lime of various proportions and analyzed the overall stability of the embankment and the lime-stabilized soft soil foundation considering different thicknesses of the overburden. Based on the results, the following major conclusions were drawn:

- The undrained shear strength of the lime-stabilized soils, which was cured for a period of 28 days increased from 97 kPa for 3% lime content to 198 kPa for 12% lime content. This strength gain signifies an improvement in the engineering properties of the soft soil foundation, and thus can be related to a significant reduction in plasticity index and swelling potential.
- Considering the economic implications of lime stabilization and the overall stability of the highway project, this study recommends stabilizing the soft soil foundation with 10% lime content to a maximum depth of 3 m.

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