ABSTRACT

The main aim of this research is to investigate the broadening of highway embankments using vertical piles towards the drains or canals slope to avoid land acquisition process. In Egypt, many problems have been ensued owing to narrow highways subjected to a continuous increase of traffic volume. Accordingly, general Authority of Roads and Bridges was obliged to develop the highways, especially, at agricultural cities such as Delta highway networks as well as Upper Egypt ones in the vicinity of the river Nile. The development of ongoing highways was considered in this research which is considered to be a portion of the national highways project launched by the Egyptian government on 2014. Stability analysis was carried out using commercial software package PLAXIS 2-D version 8.2 non-linear. PLAXIS is a finite element program that has been developed specifically for the analysis of deformation and stability in geotechnical engineering problems. A two-dimensional finite element PLAXIS 2-D was used to model the widening of the highway using vertical piles. Simulation of soil non-linearity was obtained using the Mohr-Coulomb constitutive model. The results elucidated that the piles location and piles length had significant influence on the failure modes and factor of safety.

Keywords: Highways, finite element, overall Stability, piles.

1. INTRODUCTION

In Egypt, several train accidents had occurred in the last decades that led to the loss of human lives in the period from 1993 to 2010. Such disasters usually took place in the third-class passenger trains used by the majority of low-income personnel with several accidents at the freight trains as well. The deterioration of the rolling stocks together with the remarkable decline in developing the rails and signaling system led to an eventual decrease of the service level and prolongation of the trip time, resulted in an ultimate lack of confidence of the public in the railways. The majority of passengers and stakeholders shifted to the use of land transportation as recorded in all the national transportation studies in the last decade (JICA-MINTS-2012). Accordingly, the traffic capacity has been increased earssplittingly on several highways, especially the agricultural highways that are often located beside the canals or drains. The general Authority of Roads and Bridges had developed the highways to increase their capacity in many provinces. These developments led to the expansion of the highways towards the canals in many areas that significantly caused a modification in the slope angle even at other areas the berm of canal's slope had been scraped out such as the highway zone that has been studied in this research. Luxor-Aswan highway is a vital highway in upper Egypt, located approximately 650 Km south of Cairo as shown in Figure 1.

![Figure 1: Location of the highway under study.](image-url)
2. SUBSOIL INVESTIGATION

A subsurface investigation consisting of two boreholes @ 200 m along the road at 15.0 ms depth and relevant laboratory tests were planned and implemented to establish the subsoil profile and obtain necessary physical and mechanical soil parameters. The locations of the boreholes and the interpreted subsoil profile are shown in Figure 2. In general, the subsoil at the widening of the highway area can be simplified into two main strata. The upper layer is soft to medium stiff silty clay and the lower layer is medium to dense sand as shown in Figure 2. Thickness of the silty clay layer is about 9.8m from the top level of the highway while the sand layer extended to the end of boreholes. A series of tests was carried out. These tests can be categorized into two groups; field tests including the standard penetration test (SPT) for the sand layer and laboratory tests including the unconfined compression strength (qu), consolidated drained triaxial test (CD) and Atterberg limits for the silty clay layer. The ground water level measured in boreholes is approximately same as water level in the contiguous Canal that flows parallel to the proposed widening of the highway. As informed by responsible authorities; the high water level is (+8.20) and the low water level is (+5.22) as shown in Figure 2. Soil properties interpreted from the field and laboratory tests can be summarized as given in Table 1.

3. PROPOSED BROADENING OF HIGHWAY

3.1 Several methods of widening of highway embankments are available today. These methods may be appropriate to widen the highway in single or combination form. There are many factors that should be considered to determine the suitable method in the broadening process such as soil conditions and site constraints. In the highway widening, the slope crest is road grade and the toe of slope is contiguous to the water canal, hence, the crest can not be modified, additional mass can not be placed to the toe of slope. The old berm of canal’s slope was cancelled and filled by crushed stone as shown in Figure 3.

3.2 The highway was widened to be 9.00 m instead of 5.00 m. In addition, the tangent piles were chosen as the most realistic method that can be installed quickly and provide immediate strength improvements without completely closing the highway. For this widening, one row of tangent piles is chosen for widening of the highway. The diameter of piles considered in the analysis is 0.50 m with center-to-center spacing between adjacent piles of 0.60 m. These piles are connected with a rigid capping beam at the top, which assists equitable pressure distributions in piles as shown in Figure 3. The capping beam of 0.60 x 0.60 m size is used along the alignment of the piles. The total length of tangent piles and the penetration depth in the sand layer are 13.0 m and 3.20 m respectively, as shown in Figure 3.

4. METHOD OF ANALYSIS

Overall Stability analysis has been performed using PLAXIS to model the widening of the highway using tangent piles. The plane-strain model and 15-node element were selected for 2-D analysis. Mohr-Coulomb constitutive model was chosen for simulation of the subsoil layers. The Mohr-Coulomb is an elastic-plastic model which is often used to model
soil behavior in general and serves as a first-order model. The lower sand layer is modeled in drained condition while the silty clay is modeled in undrained condition. The soil properties can be summarized as shown in Table 1.

![Figure 3 Proposed widening of Naga-Hammdi highway](image)

**Table 1**: Summary of material properties of silty clay, sand and fill layer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Silty clay</th>
<th>Sand</th>
<th>Fill</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{\text{sat}}$</td>
<td>16.00</td>
<td>17.00</td>
<td>18</td>
<td>KN/m$^3$</td>
</tr>
<tr>
<td>$\gamma_{\text{sat}}$</td>
<td>18.00</td>
<td>20.00</td>
<td>20.00</td>
<td>KN/m$^3$</td>
</tr>
<tr>
<td>$K$</td>
<td>8.640E-04</td>
<td>0.86</td>
<td>0.86</td>
<td>m/day</td>
</tr>
<tr>
<td>$E'$</td>
<td>5800</td>
<td>23000</td>
<td>22000</td>
<td>KN/m$^2$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.35</td>
<td>0.30</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>$C'$</td>
<td>11.50</td>
<td>1.00</td>
<td>1.00</td>
<td>KN/m2</td>
</tr>
<tr>
<td>$\phi'$</td>
<td>18.30</td>
<td>36.00</td>
<td>38</td>
<td>deg.</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>0.00</td>
<td>6.00</td>
<td>6.00</td>
<td>deg.</td>
</tr>
<tr>
<td>$C_u$</td>
<td>19.50</td>
<td>0.00</td>
<td>0.00</td>
<td>KN/m$^2$</td>
</tr>
</tbody>
</table>

Where:
- $\gamma_{\text{sat}}$: Soil unit weight above G.W.T.
- $\gamma_{\text{sat}}$: Soil unit weight below G.W.T.
- $K$: Coefficient of permeability.
- $E'$: Young's modulus.
- $\nu$: Poisson's ratio.
- $C'$: Cohesion.
- $\phi'$: Friction angle.
- $\Psi$: Dilatancy angle.
- $C_u$: Undrained shear strength.

PLAXIS introduce three ways of modeling undrained behavior. The silty clay layer is modeled in undrained behavior by selecting the effective strength parameters ($c'$, $\phi'$) and the effective stiffness parameters ($E'$, $\nu'$). This can be done as PLAXIS can transform the effective parameters ($E'$, $\nu'$) into undrained parameters ($E_u$, $\nu_u$). The advantage of this way is that PLAXIS distinguishes between effective stresses and excess pore pressures. The tangent piles and capping beam are represented as plate elements. Plate elements in two-dimensional finite element model are composed of beam elements with three degrees of freedom per node: two translational degrees of freedom ($U_x$, $U_y$) and one rotational degree of freedom (rotation in the x-y plane). When using a 15-noded soil element, 5-noded beam elements are used. The beam elements are based on Mindlin's beam theory. Therefore, this allows for beam's deflection due to shearing as well as bending. For modeling of the tangent piles and capping beam as a beam element, basic input parameters are required; the parameters are normal stiffness, $E_A$, flexural rigidity, $E_I$ and Poisson's ratio, $\nu$. For Plane-strain model, the values of $E_A$ and $E_I$ are related to stiffness per unit width in the out-of-plane direction. The beam element is modeled as a linear-elastic behavior. Interface elements are used for modeling soil-structure interaction for the tangent piles. They allow relative movements at the soil-structure interface. Interface also is used for reducing the strength.
between the soil and the structure. The interface value for clay/concrete and sand/concrete is taken as 0.7 and 0.8 respectively. The input parameters of tangent piles in PLAXIS program can be summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tangent piles</th>
<th>Capping beam</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavior</td>
<td>Elastic</td>
<td>Elastic</td>
<td>-</td>
</tr>
<tr>
<td>EA</td>
<td>7195833</td>
<td>13200000</td>
<td>(KN/m)</td>
</tr>
<tr>
<td>EI</td>
<td>112435</td>
<td>396000</td>
<td>(KN.m2/m)</td>
</tr>
<tr>
<td>v</td>
<td>0.15</td>
<td>0.15</td>
<td>-</td>
</tr>
</tbody>
</table>

The number of finite elements in the mesh has an important effect on the precision of the analysis. Therefore, the degree of coarseness of the mesh was tuned after many trials of analysis using different degree of coarseness, until refinement of the mesh does not almost affect the results of analysis. The completing model of the highway is presented in Figure 4. A uniformly distributed traffic load of 20 KN/m² is applied along the road width according to AASHTO (LRFD)-2007.

5. RESULTS OF ANALYSIS

For calculation, the initial stress conditions are calculated using the gravity load procedure due to the inclined layering of the model. The water table is initially considered at high level and the water pressure is generated. Staged construction is applied activating traffic load, then sudden drawdown of the water level with filling zone only and with filling zone and tangent piles. After the plastic calculation, safety analysis is carried out employing the φ-c reduction method to calculate a global factor of safety. After the strength of the model has been reduced until failure occurs in the soil body, the slip surface can be inspected in several ways. The incremental shear strain calculated from the φ-c reduction procedure is a good indication of the slip surface of the slope. As shown in Figure 5, the slip surface obtained from filling zone only was developed as a toe failure while the slip surface obtained from the filling zone and tangent piles was developed as a deep-seated failure.

![Highway model](image)

**Figure 4** Highway model

**Figure 5** Computed slip surface (a) Filling zone only. (b) Filling zone and tangent piles

Failure mechanism was identified in the finite element model using Phi-c reduction option in PLAXIS to compute
safety factor. In the Phi-c reduction approach, the strength parameters \( \tan \varphi \) and \( c \) of the soil are successively reduced until failure occurs. A global factor of safety using Phi-c reduction approach can be measured, if failure is reached in the model. The strength reduction is run until the model factor of safety forms a plateau when plotted against the point displacement. This is shown for two cases in Figure 6. The recommended factor of safety due to the sudden drawdown of the water level is 1.20 (National Research Council, 1983).

![Figure 6](image_url)

**Figure 6** Factor of safety at sudden drawdown stage for two cases considered

6. PARAMETRIC STUDY

Numerical analysis was conducted to investigate all parameters that affect the widening of highway embankments using tangent piles. The parametric study is based on the geometry of Nagaa-Hammadi highway for the sudden drawdown stage. The properties of soil and tangent piles are considered in the analysis as explained in the preceding paragraphs. The parameters considered in the analysis are piles location and piles length.

6.1 Piles Location

The effect of piles location is conducted to find out the appropriate location of piles that provides maximum factor of safety. The location of piles is considered as a ratio of \( X_0/X_t \), where \( X_0 \) is the horizontal distance from the toe of slope to the piles and \( X_t \) is the horizontal distance from the toe of slope to the crest of slope as shown in Figure 7. The different values of \( X_0/X_t \) ratio considered in the analysis are 0.0, 0.25, 0.50, 0.75 and 1.0.

![Figure 7](image_url)

**Figure 7** Schematic views of piles.

The mode of failure that is identified automatically from the shear strength reduction technique for the various piles locations is presented in Figure 8. Based on the results obtained from the shear strength reduction technique, the observations and discussions can be summarized as follows:

- In range of \( X_0/ X_t \) ratio from 0.0 to 0.25, the slip surface was developed above the piles tip as a shallow failure.
- In range of \( X_0/ X_t \) ratio from 0.50 to 1.0, the slip surface was almost developed below the bottom of the piles.
The slip surface path decreased gradually with the increase in $X_o/X_t$ ratio from 0.5 to 1.0. The factor of safety is determined based on the potential slip surface obtained from the shear strength reduction technique. Figure 9 represents the effect of piles location ($X_o/X_t$) on the factor of safety.

Figure 8 Incremental shear principal directions showing the slip surface of the slope (a) $X_o/X_t = 0.00$. (b) $X_o/X_t = 0.25$. (c) $X_o/X_t = 0.50$. (d) $X_o/X_t = 0.75$. (e) $X_o/X_t = 1.00$.

Figure 9 Influence of piles location on Factor of safety.
From this Figure, the observations and discussions can be summarized as follows:

- The variation in location of piles has noticeable influence on the factor of safety.
- The maximum factor of safety is evident at Xo/Xt ratio of 0.5. This could be due to the potential slip surface obtained from Xo/Xt ratio of 0.5 that has a longer path in comparison with the other slip surfaces.

6.2 Piles Length

The influence of piles length on the factor of safety and the behavior of pile should be investigated. The pile length is defined as a ratio of X/L, where L is the embedded length of pile in silty clay layer and X is the penetration depth of pile in the sand layer as shown in Figure 10. The values of X/L ratio considered in the analysis are 0.25, 0.50, 0.75, 1.00 and 1.25 for the piles located at the middle of slope.

The mode of failure that is identified automatically from the shear strength reduction technique for the variation in piles length is presented in Figure 10. The following observations and discussions are based on the results obtained from the shear strength reduction technique:

- The slip surface was noticeably influenced by the change in piles length.
- The slip surface was almost developed below the bottom of the pile as a deep-seated failure at X/L ratio from 0.25 to 0.75.
- The slip surface was developed above the pile tip as a shallow failure at X/L ratio from 1.0 to 1.25. This is because the slip surface needed high energy to pass below the piles at X/L ratio from 1.0 to 1.25, hence, the slip surface was rapidly converted to a shallow failure.
- As X/L ratio increased from 0.25 to 0.75, the slip surface path gradually increased.

Figure 10 Incremental shear principal directions showing the slip surface of the slope at Xo/Xt ratio of 0.5. (a) X/L = 0.25. (b) X/L = 0.50. (c) X/L = 0.75. (d) X/L = 1.00. (e) X/L = 1.25.

The factor of safety calculated based on the potential slip surface obtained from shear strength reduction technique. Figure 11 illustrates the effect of the variation in piles length on the factor of safety. The following observations and discussions are concluded from this Figure:
The factor of safety was markedly influenced by the change in piles length. As X/L ratio increased from 0.25 to 1.0, the factor of safety noticeably increased linearly by about 33.41%. The reason is, with the increase in X/L ratio, the slip surface path gradually increased, leading to an increase in the factor of safety.

As X/L ratio increased from 1.0 to 1.25, the factor of safety was almost constant. This is quite logical, because a similar slip surface was observed at X/L ratio from 1.0 to 1.25, resulting the same factor of safety.

![Figure 11 Influence of piles location on Factor of safety.](image)

7. CONCLUSIONS

The following conclusions were postulated based on the different results of investigations that were presented in this research:

- The broadening process using the tangent piles showed a good improvement for critical highway's embankment.
- The slip surface changed according to the change in piles location. The slip surface obtained from the piles located after the middle of slope toward the toe of slope was developed as a shallow failure, while the piles located at the middle of slope toward the crest of slope was developed as a deep-seated failure.
- When the X/L ratio increases from 0.25 to 0.75, the slip surface gradually increases below the bottom of piles as a deep-seated failure. When it increases 1.00 to 1.25, the slip surface becomes a very shallow failure above the piles tip.
- The piles location at the middle of slope achieves the highest factor of safety.
- When the X/L ratio increased from 0.25 to 1.00, the safety factor increased by 33.41%. When it increased more than X/L ratio of 1.00, the safety factor remained constant.

References


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Hisham Arafat received the B.S. and M.S. degrees in Structural Engineering from Ain-Shams University, Egypt 1985 and 1991, respectively. During 1993-1997, he got a PhD scholarship to Germany and got the degree on 1998. He works in the consultation, design and rehabilitation of infrastructures as bridges, underpasses, tunnels,…etc and currently working as the head of structural Engineering department in Furtle University in Egypt.