Prediction of Heave of Expansive Clay Reinforced with Granular Pile Anchors

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ABSTRACT

Expansive soils are considered to be one of the most problematic soils. Structures, especially the lightly-loaded ones, founded in these soils, experience distress and develop cracks due to the alternate swelling and shrinkage of the soil. In the dry state, the bearing capacity of the soil will be high but in the swollen state, it decreases quite appreciably. Granular piles, anchored at the bottom to a steel plate, through a steel rod fastened to the surface footing, are called granular pile-anchors. Their efficacy in reducing heave, when used to reinforce expansive soil beds, was already established through laboratory and field studies. From the results of the laboratory investigations, multiple linear regression analysis has been performed in this paper, using the various independent variables, for determining the swelling potential of the reinforced soil. The validity of the above correlation has been checked by conducting experiments with variables other than those used in the laboratory investigations. Using the correlation, the swelling potential of the expansive soil, reinforced with granular pile-anchors, can be predicted.

1. INTRODUCTION

Expansive soils, popularly known as black cotton soils in India, undergo alternate swelling and shrinkage on imbibitions of water and evaporation and evapotranspiration thereof. This results in the development of cracks in buildings and other structures like retaining walls, canal beds and linings, highways etc. founded in them or supporting them. Several researchers suggested methods to overcome or mitigate the problems associated with expansive soils over the last few decades. They include sand cushions (Satyanarayana, 1969), CNS cushion (Katti, 1979), underreamed piles (IS 2911 – Part-III, 1980) etc. Many of them, however, have certain limitations (Babu Shanker et al, 1980; Subba Rao, 2000). Keeping these short-comings in view, a simple foundation technique was developed in the name of granular pile-anchors (Phani Kumar et al., 2004).

2. GRANULAR PILE-ANCHORS

Granular piles, also known as stone columns, have been extensively used in soft clays and loose sands to ameliorate their geotechnical properties (Greenwood, 1970; Hughes and Withers, 1974). A granular pile is good in compression but not in tension. Hence, it cannot be adopted in expansive soils. As the soils undergo swelling, the particulate medium gets sheared off easily. A modification to the granular pile was suggested (Rao, 1986) in the form of a granular pile-anchor but not supported with experimental evidence. In this, the foundation is anchored to a mild steel plate provided at the bottom of the granular pile. This becomes tension – resistant and prevents the particulate medium from getting sheared away by the swelling soil surrounding it. The various forces acting on the granular pile – anchor are shown in Fig. 1.
The uplift force, U, is caused by the vertical swelling pressure acting on the annulus between the edge of the granular pile-anchor (GPA) and the edge of the foundation footing.

\[ U = \sigma_s \frac{\pi}{4} (D_f^2 - D_{gp}^2) \]

Where, \( \sigma_s \) is the swell pressure
\( D_f \) is the diameter of the foundation
\( D_{gp} \) is the diameter of the granular pile.

The resisting forces comprise:
(i) The self-weight of the granular pile
(ii) The frictional forces generated along the surface area of the granular pile.

The latter component, in turn, is a result of
(a) The lateral pressure caused by the self-weight of the soil surrounding the pile = \( K \sigma_{VO} \)
(b) the lateral swell pressure caused by the expansive soil \( (K_s \sigma_s) \)

Where \( K \) is the later earth pressure coefficient
\( \sigma_{VO} \) is the effective vertical overburden pressure
\( K_s \) is the coefficient of lateral swell pressure.

From field studies granular pile-anchors have been found to be efficacious in minimizing heave (Srirama Rao et al., 2008) and improving the load-carrying capacity in compression (Phani Kumar et al., 2008) and uplift (Srirama Rao et al., 2007), in addition to the observations made in laboratory model studies (Phani Kumar et al., 2004). The frictional forces developed along the surface of the GPA are responsible for reducing heave as well as improving the load-carrying capacity in both compression and uplift.

From the model studies (Phani Kumar et al., 2004), in addition to the above findings, an additional conclusion that the increase in the relative density (\( D_r \)) of the granular pile causes increase in the frictional resistance along the surface of GPA, was also drawn.

3. MATHEMATICAL FORMULATION

Results of the laboratory model swell tests on the expansive soil whose FSI, the free swell index, is 190%, reinforced with GPAs are shown in Table 1. A FSI value of 190% indicates that the soil has a HIGH degree of expansiveness. The independent variables whose effect has been studied include:

\( \gamma_d \) - dry unit weight of the expansive clay, kN/m³
\( D_r \) - relative density of the pile material
\( L \) - pile length in mm
\( D_{gp} \) - pile diameter in mm
\( D_f \) - diameter of the footing in mm

The dependent variable is \( S' \), which is the swelling potential of the expansive clay reinforced with GPA.

Swelling potential is defined as the ratio of the increase in the thickness (heave) to the initial thickness of the soil sample, expressed as a percentage.

An attempt was made to develop a general expression for the swelling potential, which is the dependent variable, as a function of \( D_r \), \( D_f/D_{gp} \) and \( L_f/D_{gp} \), which are the independent variables. Multiple linear regression analysis was performed for this purpose.

The general equation is

\[ S' = a + b \gamma_d + c D_r + d \left( \frac{D_f}{D_{gp}} \right) + e \left( \frac{L_f}{D_{gp}} \right) \]

Where \( a \) is a constant and \( b \) to \( e \) are coefficients.

Rewriting the independent variables as
\( \gamma' = X_1, \ D_r = X_2, \ D_f/D_{gp} = X_3 \) and \( L_f/D_{gp} = X_4 \)

Eq. (1) may be written for convenience as

\[ S' = a + b X_1 + c X_2 + d X_3 + e X_4 \] (1a)

The equations used for the regression analysis are:

\[ \sum S' = a \sum N + b \sum X_1 + c \sum X_2 + d \sum X_3 + e \sum X_4 \] (3)

\[ \sum X_1 S' = a \sum X_1 X_1 + b \sum X_1 X_2 + c \sum X_1 X_3 + d \sum X_1 X_4 + e \sum X_1 X_4 \] (4)

\[ \sum X_2 S' = a \sum X_2 X_1 + b \sum X_2 X_2 + c \sum X_2 X_3 + d \sum X_2 X_4 + e \sum X_2 X_4 \] (5)

\[ \sum X_3 S' = a \sum X_3 X_1 + b \sum X_3 X_2 + c \sum X_3 X_3 + d \sum X_3 X_4 + e \sum X_3 X_4 \] (6)

\[ \sum X_4 S' = a \sum X_4 X_1 + b \sum X_4 X_2 + c \sum X_4 X_3 + d \sum X_4 X_4 + e \sum X_4 X_4 \] (7)

Solving equations (3) to (7) by the Gauss-Seidel matrix inversion technique, constants a to e can be evaluated.

The coefficient of correlation,

\[ r = \sqrt{\frac{\text{Explained Variation}}{\text{Total Variation}}} \]

Where, explained variation =

\[ a \sum S' + b \sum X_1 S' + c \sum X_2 S' + d \sum X_3 S' + e \sum X_4 S' - \frac{(\sum S')^2}{N} \] (8)

Total variation = \( \sum S'^2 - \frac{(\sum S')^2}{N} \) (9)

and \( N \) is the number of tests.

4. ANALYSIS

The swelling potential of the untreated soil with an initial moisture content of 14% at dry unit weights \( \gamma_d \) of 13.0, 14.0 and 15.0 kN/m³ were found to be 6%, 9% and 14% respectively. The swelling potential of the soil increases with an increase in its dry unit weight. This is because, as \( \gamma_d \) is high, the number of particles in the expansive soil is more. Greater surface area is thus available which gives greater scope for accumulation of water around the soil particles and a consequential increase in swelling. Thus, \( \gamma_d \) is an important parameter as can be seen from Table-1.
The swelling potential decreases significantly following the installation of the GPAs.

It can be further seen from the table that, for a given diameter of the GPA, \( D_{gp} \), the swelling potential decreases with an increase in the pile length. That is, for a given pile diameter, as the ratio \( L_{gp} / D_{gp} \) increases, the swelling potential decreases. Likewise, for a given pile length, \( L_{gp} \), the swelling potential decreases with an increase in the diameter of the pile. Thus, for a given pile length, as the ratio \( L_{gp} / D_{gp} \) decreases, the swelling potential decreases. Thus, the ratio \( L_{gp} / D_{gp} \) is another important parameter in the study of the efficacy of GPA in reducing the swelling potential of the soil.

As \( D_{wp} \), on which the footing is placed is increased the annular area of the footing on which the swell pressure acts is reduced. Therefore, the uplift force, which is the product of the swell pressure and the annular area decreases. Thus, the normalized ratio, which is the ratio of the diameter of the footing to that of the granular pile, \( D_f / D_{wp} \), becomes yet another important parameter.

The relative density (\( D_r \)) of the material of the granular pile also has been found to have an effect on the swelling potential. The denser the packing of the particles in the pile material the higher will be the angle of internal friction at the pile-soil interface, which results in a reduced swelling potential. Thus, \( D_r \) is another important parameter to be considered.

All the above independent variables are considered in the analysis. By solving the equations for \( S_2 \), the following constants were obtained: \( a = -4.26; b = 0.343; c = -1.151; d = 0.739; e = -0.066 \). Thus, the general expression for the reduced swelling potential for the given soil at the given water content is

\[
S_2 = -4.26 + 0.343 \gamma_d - 1.151 D_r + 0.739 \left( \frac{D_f}{D_{wp}} \right) - 0.066 \left( \frac{L_{wp}}{D_{wp}} \right)
\]

Thus, for a given expansive soil, it should be possible to predict its swelling potential for any placement conditions and varied lengths, diameters and relative density values, when reinforced with a GPA.

To verify the validity of the correlation, swell tests were conducted in model test tanks in the laboratory, using the same soil, but varying the other independent variables. The dry unit weight of the soil was taken as 14 kN/m\(^3\). Variables: \( D_r \) of the GPA material: 0.4, 0.7; pile length, \( L_{wp} = 200 \) mm; pile diameter, \( D_{wp} = 40 \) mm and 50 mm, \( D_f \), foundation plate diameter = 80 mm. Table 2 shows the observed values in the model tests and the predicted values. It can be seen from the table that the values agree closely, establishing the validity of the correlations developed.

<table>
<thead>
<tr>
<th>Table 2: Comparison of the Predicted and the Observed Value of Swelling Potential of GPA – Reinforced Expansive Soil</th>
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</thead>
<tbody>
<tr>
<td>Dia. ( D_{wp} ) (mm)</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Predicated</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
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5. CONCLUSIONS

A general expression for the swelling potential of the given expansive soil at an initial water content of 14%, reinforced with a granular pile-anchor, can be given in the form of Eq.
10. A good correlation was obtained with the above expression.

REFERENCES


