Settlement Analysis of Axially Loaded Vertical Piles in Cohesive Soil

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ABSTRACT

The mechanism of load-transfer from axially loaded pile to soil and the corresponding settlement is an important aspect of pile foundation. Due to the visco-elastic nature of clay the settlement of piles is time dependent. In the present work, a model has been developed to predict the settlement of piles subjected to axial loads. For analysis, the soil pile system is represented by a rheological visco-elastic non-linear Kelvin model. The strain softening effect of creep in plastic soil has been attributed to the spring while the increase in soil resistance with time has been simulated by the dash pot. An attempt has been made to determine the rheological constants used in the proposed model from the laboratory experiments for a particular pile soil system. A comparison of predicted settlement of piles to the observed settlement of piles is made, which shows a good agreement up to a limited range of loading.

1. INTRODUCTION

Stress strain characteristics of soil are very complex due to the inherent non-homogeneity and non-isotropy in the soil mass in field. Poulos and Davis (1968) and Butterfield and Banerjee (1971) obtained analytical solutions for the settlement behaviour of an axially loaded single pile in an elastic medium by considering the uncompressible and compressible pile as a number of uniformly loaded cylindrical segments together with a uniformly loaded base respectively. Prakash (1962) gave a simple approach to study behavior of group piles subjected to lateral load.

In the present study, a non linear Kelvin model is assumed to describe the visco-elastic behavior of soil-pile system under the application of axial load. The rheological model consists of a non linear spring and a dash pot connected in parallel. The spring takes into account the strain softening effect of creeping plastic soil. The dash pot with a non linear time thickening structural viscosity, simulate the increase in viscous resistance with time. The proposed rheological model is adopted to simulate the mechanism of deformation of axially loaded pile embedded in soft cohesive soil.

Figure 1 shows an axially loaded pile resting on the proposed model foundation representing the visco-elastic behavior of the plastic soil mass. The total load \( P \) applied at the pile top is transferred to the soil media as skin friction \( P_s \) and point load \( P_p \). Assuming no elastic deformation in pile i.e. the net load at the tip of pile is responsible for the time-dependent deformations of the soil-pile system. So in the proposed rheological model the deformation occurs under influence of point load \( P_p \). The axial force per unit area for a pile of cross sectional area ‘a’ will be \( P_p/a \).

Therefore, \( P_1 = \frac{P_p}{a} \)

The differential equation with respect to time for the proposed rheological model is given by the equation,

\[
p_1 = K_1 S_i + n_1 \frac{dS_i}{dt}
\]

(1)

Where, \( S_i \) is the time dependent pile tip displacement.

In the proposed model this displacement is due to the deformation of dashpot representing the time thickening viscosity. The spring of the model is assumed as a strain softening spring to take accounts the creeping effect of the cohesive soil.

The stiffness of the spring \( K_1 \) decreases as the deformation increases. It is defined as,

\[
K_1 = \frac{1}{S_i} \frac{K_0}{a}
\]

(2)
Where, $K_0$ is a spring constant.

$$K_1 = \frac{1}{S} \cdot \frac{K_0}{a}$$  \hspace{1cm} (2)

$$n_t = n_0 t^m$$  \hspace{1cm} (3)

Therefore, the differential equation to describe the deformation of the model can be written as,

$$\frac{p_p}{a} = \frac{K_0}{a} + n_0 t^m \frac{dS_t}{dt}$$  \hspace{1cm} (4)

The deformation with respect to time $t$ is obtained by solving the above equation as,

$$S_t = \frac{p_p - K_0}{a n_0} \cdot \frac{t^N}{N}$$  \hspace{1cm} (5)

Where, $N = (1-m)$.

This relationship can be solved knowing the rheological constants i.e. $K_0$, $n_0$ and $N$. The proposed derived time-load-settlement relationship may be used to predict the settlement behaviour of the axially loaded vertical piles embedded in cohesive soil with respect to time. The settlement obtained by this relationship continues to increase at a decreasing rate and approaches an asymptote under a given load. Thus, the rheological constants, and $N$ of the proposed relationship for the time-load-settlement of the axially loaded vertical pile remain constant during the process of settlement under applied load. However, these constants vary with the soil type, soil consistency and type of pile.

2. NEED FOR MODEL STUDY

In the present research work experimentally obtained time-settlement data were used to determine the rheological constants required to predict the time-load-settlement relationship for axially loaded piles in cohesive soil.

**Choice of Soil**

Locally available clay found at a depth of 1.5 m depth below the ground level was taken for the model studies. Engineering properties of the clay is given in the Table 1.

**Table 1: Properties of Clay**

<table>
<thead>
<tr>
<th>Type of Soil</th>
<th>CL (IS 1498-1970)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay fraction</td>
<td>14%</td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>33%</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>21%</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>12%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.60</td>
</tr>
<tr>
<td>Color</td>
<td>Yellowish</td>
</tr>
<tr>
<td>Undrained Compressive strength</td>
<td>0.048 kg/cm²</td>
</tr>
<tr>
<td>Unconfined Compressive strength by vane shear test at 31.02% Moisture Content</td>
<td>0.05 kg/cm²</td>
</tr>
</tbody>
</table>

**Piles**

In model testing largest size of the pile is preferred for the better results. Keeping in view the feasibility of model testing program the main factors that govern the dimensions of model pile are, i) The consistency of clay and ii) The magnitude of load. In the present model study three different aluminum pile sections were used. The external diameter of these piles was 1 cm, 1.9 cm and 2.5 cm respectively. The length of each pile was 27 cm. Value of Young’s Modulus of pile material ($E$) was determined experimentally by transverse load testing machine. Point load was applied at the centre of the aluminum rod of which the pile was made. The distance between the supports was fixed as 30.48 cm. Load applied and the corresponding deflection obtained was recorded and the value of $E$ computed from observations using the relation (6) and presented in Table 2.

$$E = \frac{Wl^3}{48Iy}$$  \hspace{1cm} (6)

Where, $W$ is Point Load, $I$ is Moment of Inertia; $l$ is Length of span and $y$ is the deflection.

**Table 2: Details of Piles Used for Model Studies**

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Outer Diameter (mm)</th>
<th>L/D ratio</th>
<th>Length Embedded (cm)</th>
<th>Overall Length (cm)</th>
<th>Modulus of Elasticity kg/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>22</td>
<td>22</td>
<td>27</td>
<td>$6.1 \times 10^7$</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>12</td>
<td>22</td>
<td>27</td>
<td>$6.1 \times 10^7$</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>9</td>
<td>22</td>
<td>27</td>
<td>$6.1 \times 10^7$</td>
</tr>
</tbody>
</table>

**Experimental Study**

The size of the experimental tank for model studies was decided keeping in view the length and size of piles to be
tested. The length was calculated by allowing a zone of influence of 5 piles diameter around a pile and such that it could accommodate all the piles to be tested at a time properly. The depth was fixed by providing a minimum thickness of 5 pile diameter below the tip of pile. A rectangular tank of inside dimensions (47.5 x 24 x 35) cm was used for experiment. The tank was made up of a form timber board. The joints were properly sealed by aluminum plates. The clay deposit must be homogenous and uniform with regard to moisture distribution and density to achieve reproducible and comparable results. Sun dried powdered clay passing through I.S. sieve No. 425 micron was used for filling the model tank.

**Installation of Piles**

The piles were driven inside the soil by means of a screw jack. The screw jack was slowly operated and the pile was driven at a rate of about 0.075 mm/sec. This slow rate of driving the pile was selected so as to impart minimum disturbance to the adjacent soil. 22 cm of the length of pile from the tip was inserted with its vertical axis perpendicular to the bed of the soil in the tank after installing the piles in position the experimental tank was kept as such for a period of 24 hours to allow for thixotropic hardening (Singh, 1972). Pile loading device was designed in such a way that the load comes axially on pile. The load was transferred to the pile top through the ball as an axial point load. Total weight of the loading frame was 490 gms. The time dependent settlement under the static load was recorded for a period of 24 hours. Each load was kept for 24 hours. The settlement occurred under each load was recorded at the following intervals 0, 10, 50, 100, 200, 300, 400, 500, 600, 700, 800, 1360, 1440 minutes.

3. **PILE TESTING**

After allowing the clay to overcome the disturbance caused by driving of piles, the pile testing was started. Each pile was given three load increments. Dial gauge reading with respect to specific time and loads were recorded for each pile.

**Soil Sampling and Strength Tests**

After the pile load tests were over on all the piles the piles were removed. Density and moisture content variations were checked. Undisturbed sample from the experimental tank was taken in sampling tube from undisturbed zone of soil for carrying out unconfined compression test. Laboratory vane shear tests were also performed for determining the undrained shear strength of clay deposit in the tank.

4. **TEST RESULTS AND DISCUSSIONS**

**Shear Strength of Clay**

The results of laboratory vane shear tests carried out on the samples collected from the experimental tank shows no significant difference in the shear strength of the entire clay deposit before and after test and the average value of the shear strength was 0.051 kg/cm². The value of undrained shear strength ‘c_u’ from unconfined compression test comes out to be equal to 0.047 kg/cm².

**Load Settlement Behaviour of Piles**

Figure 2 shows the load- settlement behaviour of 19 mm diameter pile. The first load in each case was applied and maintained for 24 hours. The final settlement observed after 24 hours was plotted against the load. Similarly, the next increment was maintained for 24 hours and settlement observations were taken. Only three increments were applied. The load-settlement data indicate general pattern of load-settlement behaviour of piles in clay.

**Determination of Rheological Model Parameters for the Soil Pile System**

Experimentally obtained time-settlement data were used to determine the rheological constants required to predict the time-load-settlement relationship for axially loaded piles in cohesive soil.

A series of tests were performed on axially loaded vertical piles embedded in soft cohesive soil. Settlement with respect to time was observed to study the time-dependent behaviour under applied load. The test data were plotted on an arithmetical scale to show the increase in settlement with time under sustained axial load for pile diameter 10 mm, 19 mm, 25 mm respectively. These observations lead to the conclusion that the time dependent settlement under axial load initially increase rapidly, continues with a rapid decreasing rate and finally with a slow decreasing rate extends asymptotically. This behaviour indicates that under such a system, specific values of initial and final settlement can not be ascertained. In general, these observations must be related to time.

The s-t plots are straight lines. These figures suggest that the proposed time-load-settlement relationship can be written as

\[ s = A.t^n \]  

(7)

Where,  

\[ A = \frac{p_r - K_0}{a_n N} \]
Thus, from the settlement-time plot on log-log scale $N$ and $A$ can be determined. The slope of settlement-time line provides the value of $N$. The value of $p$ is worked out using the method suggested by Coyle and Reese (1966). The value of $A$ is obtained by solving above equation. The rheological constants $K_0$ and $n_0$ are obtained by solving above equation for three different settlement-time plots for same pile. Thus, all the three rheological constants $K_0$, $n_0$ and $N$ of time-load-settlement relationship can be determined.

5. OBSERVED AND PREDICTED TIME-DEPENDENT BEHAVIOUR OF AXIALLY LOADED PILES.

The rheological constants $K_0$, $n_0$, and $N$ for the piles tested were determined. Knowing these constants, the time-load-settlement behaviour under the given load and duration of its application is predicted for pile of diameter 19mm. (Fig. 3).

It is observed that the proposed approach predicts comparable behaviour up to certain range of loading. When the axial load is increased beyond a certain range the predicted behaviour is not comparable with the observed behaviour. Thus the analysis shows that there is a close agreement between experimentally obtained and theoretically predicted $s$-$t$ curves for a limited range of loading.

6. CONCLUSIONS

The following conclusions are drawn on the basis of model studies and the analysis proposed to predict time dependent behaviour of axially loaded vertical piles in cohesive soil.

1. The time dependent settlement under static load could be represented by a straight line on log-log scale.
2. The proposed rheological non linear Kelvin model can be employed to predict the deformation pattern of soil-type system with time under axial load representing visco-elastic behaviour of soil pile system.
3. It is observed that rheological constants $N$, $K_0$, and $n_0$ remain constant for different piles subjected to different axial loads, for which the investigations were carried out.

REFERENCES


