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# Pile Capacity Estimation Considering Variability in Soil Adhesion Factor

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**Abstract.** Estimation of the ultimate bearing capacity of the pile is considered the main challenge in geotechnical engineering from a technical and economical view point. To avoid pile failure under design axial superstructure load, end bearing and skin friction capacity of the pile should be carefully estimated. Calculation of skin friction capacity of the pile for soft soils is crucial when compared to other soils. As soft soils are considered to possess less shear strength, they undergo large deformation leading to variation in skin friction capacities. This paper focuses on the estimation of skin friction capacity of pile for a cohesive soil stratum, considering the variation in adhesion factor along the depth of the strata, using PLAXIS software. As observed by many authors, the adhesion factor for soil pile is dependent on different parameters. Therefore, by the numerical modelling, the adhesion factor values calculated based on different empirical equations is validated.

**Keywords:** Adhesion factor, Skin friction, undrained shear strength, soft soils

## 1 Introduction

Any high-rise building constructed on weak-bearing soils needs a robust, deep foundation system to prevent significant settlements over time. According to Wrana.B (2015), a pile is considered to be a structural element that utilizes its end point and skin friction to transfer the axial load of the superstructure to the soil. However, the soil-pile interaction has a significant impact on a pile's skin friction capability. Large pile settlements may occur if the soil strata are composed of soft soils.

Skin friction of pile in clayey soil is calculated taking into consideration, predominantly, of soil-pile interface parameter i.e. adhesion factor, which in clay is indeed depended on the soil parameters like plasticity index, pile geometry, undrained shear strength, overburden stress etc (Cherubini, C., & Vessia, G. (2007)). Arifin et al. (2022) have analyzed the large bored pile through numerical approach (PLAXIS 2D) and confirmed that the adhesion factor of 0.97 and 0.94 for very soft and soft clayey layer soils, while 0.56 and 0.48 for stiff and very stiff clayey layer soils. Kulhaway (1989) and

Coduto (1989), in their studies, have asserted that the obtained adhesion factors for various undrained shear strength of soil are in good agreement with adhesion distribution. As per Banerjee (2022), it was found that required piled group-raft area ratio for minimizing the differential settlement of a raft in a layered soil should be within a range of 0.4 to 0.6.

A squared pile raft foundation was modeled using PLAXIS 3D for different pile lengths, spacing between piles, and a number of piles to investigate the pile behavior in terms of pile load capacity and load settlement curve under uniform vertical load. At a specific load, the settlement of the pile increases as the pile spacing increases.

Generally, the ultimate bearing capacity of a pile is determined by pile load tests. The obtained results from pile load tests can further be employed to ascertain the quality of numerical models. As per Ezzat et al (2019), three different numerical models i.e. Modified Mohr-Coulomb (MMC), Mohr-Coulomb (MC) and Soft soil models can be used to simulate the field load tests. As we know that MC model is elastic perfectly plastic model, the other two models have a non- linear relation between axial strain and deviatoric stress. The primary difference to note in these models is that stiffness in MC model is constant whereas in SS and MMC model stiffness is stress dependent. It was observed that very good agreement was found between field settlements and the calculated settlements using MMC model.

The objective of the present study is to calculate the skin friction capacity of a pile under axial loading by numerical approach (PLAXIS-3D) and compare it with the pile load test of the field. The numerical results are used to assess the accuracy of the empirical equations of adhesion factor distribution suggested by different authors.

## 2 Methodology

The skin friction of a pile for cohesive and granular soils can be determined by the analytical equation given in IS 2911 (Part 1). As the adhesion factor is dependent on various parameters, it is estimated using empirical equations suggested by them. Consequently, the skin friction of the pile is calculated by the analytical equation suggested by the IS 2911 code provision. In the present study, a bored pile of 1200 mm diameter and 25 m length is modeled using PLAXIS-3D software with an application of axial point load. The soil–pile interaction factor (adhesion factor) suggested by different authors is given as input data to find out the variation in skin friction capacity obtained from the load settlement curve, as interpreted in IS 2911 (Part 4). The load settlement curve obtained for different adhesion factor values is compared with the field load settlement curve to assess the accuracy of the adhesion factor determined as per the empirical equations.

### 2.1 Analytical Equations for estimating Adhesion Factor Values

Skin friction for cohesive soils can be estimated as per IS 2911 (Part 1), given as:

$$Q_s = \sum_{i=0}^{n}(\alpha_i * c_i * A_s) \tag{1}$$

where, $Q_s$ = ultimate skin friction; $\alpha_i$ = adhesion factor of the $i^{th}$ layer of soil strata; $c_i$ = undrained shear strength of $i^{th}$ layer strata; $A_s$ = surface area of the pile.

The values of the adhesion factor, in Eq. (1), are determined based on the empirical approaches proposed by different researchers. Please note that each empirical approach accounts for different soil properties. Thus, there is a chance to understand and signify which soil parameter has major impact on the skin friction capacity of a pile installed in cohesive soils. The various empirical approaches are given herein.

As per the API (1984), the adhesion factor is a function of undrained shear strength alone.

$$\alpha = 1 - (c_u - 25)/90 \quad \text{- when } 25\text{ kPa} < c_u < 70\text{kPa} \qquad (2)$$

$$\alpha = 1 \text{ - when } c_u <= 25\text{ kPa}$$

$$\alpha = 0.5 \text{ - when } c_u > 70\text{ kPa}$$

The adhesion factor equation proposed by Sladen (1992) is dependent on two soil parameters such as effective stress and undrained shear strength.

$$\alpha = 0.5 * (\sigma_v'/c_u)^{0.45} \qquad (3)$$

According to Karlsud (2005), the adhesion factor varies with the plasticity index of *α* clayey soils. The correlation of $c_u/\sigma_v'$ and Plasticity Index ($I_p$) with α is introduced in the form of trend lines described in the below graph:

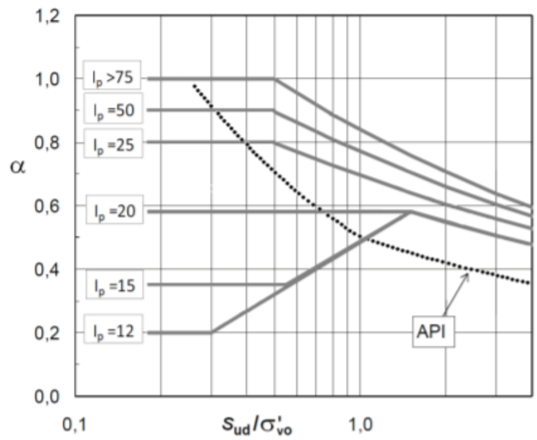


**Fig. 1 Variation of *α* with $c_u/\sigma_v'$ and Plasticity Index ($I_p$)**

The adhesion factor estimated by Kulhaway (1989) is dependent on effective stress and undrained shear strength parameters of soil:

$$\alpha = 0.21 + 0.26 * (c_u/P_a) \qquad (4)$$

$$\text{for } c_u/P_a <= 3 \text{ and } \alpha <= 1$$

Variation of α with $c_u/P_a$ and slenderness ratio (L/D) as proposed by Kolk and Van der Velde (1996) is given as:

$$\alpha = 0.5 * (D/L)^{0.2} * (c_u/\sigma_v')^{0.3} \qquad (5)$$

## 2.2 Finite Element Modeling

The pile was modeled using Plaxis-3D in layered cohesive soil whose parameters are given in **Table 1.** PLAXIS 3D is a three-dimensional program for deformation, stability, and flow analyses for different types of geotechnical applications. The program uses a comfortable graphical user interface to quickly create a geometry model and a finite element mesh. It provides different models to simulate the soil behavior which are linear elastic, Mohr-Coulomb, strain hardening, and soft soil creep models. The soil behavior is assumed to follow the Mohr-Coulomb failure criterion in the model. In PLAXIS, to simulate the Mohr-Coulomb model five parameters of soil are required. Young's Modulus (E) and Poisson's ratio (ν) are inputted as stiffness parameters and cohesion (c), Friction angle (φ), and Dilatancy Angle (ψ) are used as strength parameters. The value of these parameters are listed in Table 1.

As regards to boundary conditions, the bottom of soil body is fixed in all three directions. The side faces of the soil body are fixed in X and Y directions but free to move along the Z-direction.

The analyzed pile is cylindrical and isolated element subjected to axial loading, allowing for three-dimensional embedded pile simulation. Soil properties vary considerably from layer to layer. The embedded pile model can be used to model the pile and parameters used in PLAXIS 3D are given in Table 2. The embedded pile is connected to the adjacent soils by special interfaces named skin interfaces and foot interfaces. A point load is applied over the pile with increments and the maximum load applied is 3800 kN.

Medium mesh is selected as the optimum mesh generation element considering excessive time consumption of fine, and very fine meshes and the deformed soil body mesh is shown in Figure 3.

### Interface Modelling

The interface between soil and pile is modeled by input parameter called interface reduction factor ($R_{inter}$) [11]. If $R_{inter}$ is 1, the soil is fully bonded to the surface of pile. Interface properties indirectly depend on the soil strength. Undrained shear strength of interface can be determined by Eq. 6 and adhesion of soil-pile interface is given by Eq. 7.

$$s_{u,i} = R_{inter}\, s_{u,soil} \tag{6}$$

$$s_{a,i} = \alpha\, s_{u,soil} \tag{7}$$

where $s_{u,i}$ is undrained shear strength of interface, $s_{u,soil}$ is undrained shear strength of soil, $s_{a,I}$ is the adhesion of soil and $\alpha$ is the adhesion factor of clay.

Eq. 6 can be compared to Eq. 7 when the adhesion of soil is equal to adhesion factor multiplied by the undrained shear strength of soil. So, the $R_{inter}$ resembles the adhesion factor of soil and $s_{u,i}$ resembles the adhesion of interface (mobilized shear strength). So, $R_{inter}$ which is the adhesion factor of clay is given as input in the PLAXIS and varied for the clayey soil located at a depth of 13 m. Adhesion factor of clayey soil of thickness 5 m suggested by various authors are given in the Table 4. So, the $R_{inter}$ parameter is varied and the differences in the plot of load displacement are observed for each value of adhesion factor ($R_{inter}$).

**Table 1.** Undrained parameters of Paradip soil used in PLAXIS-3D software

| Parameter | Sand | Clay | Sand |
|---|---|---|---|
| Range of Depth (m) | 0 -13 | 13 -18 | 18 -40 |
| Material model | Mohr coulomb | Mohr coulomb | Mohr coulomb |
| Material behavior | Undrained (A) | Undrained (B) | Undrained (A) |
| $S_u$(KN/m^2) | 0 | 22 | 0 |
| Young's modulus (KN/m^2) | 8000 | 8000 | 12000 |
| Poisson's ratio | 0.33 | 0.2 | 0.33 |
| Angle of internal friction | 33 | 0 | 34 |
| Strength reduction factor | 1 | Variable - 0.27,0.52,1 | 1 |

**Table 2.** Parameters of the pile in Paradip soil

| Pile data | Value |
|---|---|
| Pile Length | 25 m |
| Pile Diameter | 1.2 m |
| E (MPa) | 29580 |
| Model of pile | Embedded beam |
| Material behavior | Linear elastic |
| Poisson's Ratio | 0.2 |

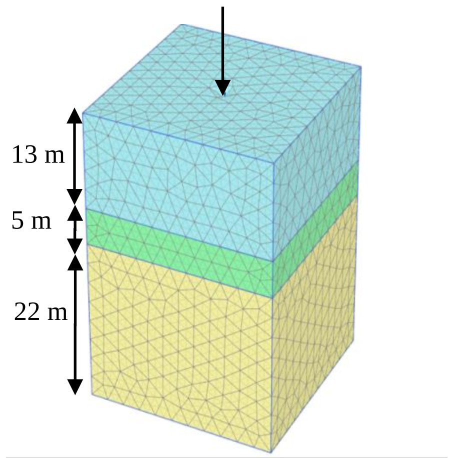


**Fig 3.1.** Deformed mesh of soil body

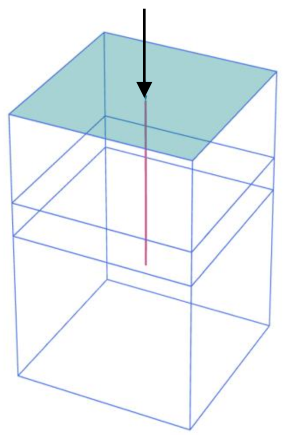

**Fig 3.2.** Pile centered in the soil

### 2.3 Pile Load Test Data

The pile load test conducted at Paradip port which is a natural deep-water port on the East coast of India in Odisha was used for the study purpose. The static load test (SLT) was performed on a cylindrical concrete pile having a length of 25 m and diameter of 1200 mm. The soil parameters based on the geotechnical investigations are given in Table 3.

**Table 3.** Bore log details of Paradip

| Depth of soil (m) | Group of soil | SPT | Cohesion (kPa) | Plasticity Index (Ip) |
|---|---|---|---|---|
| 0.5 | SM | -- | -- | -- |
| 1.5 | SM | 6 | -- | -- |
| 3 | SC | 19 | -- | 19 |
| 4.5 | SP-SM | 22 | -- | -- |
| 6 | SP-SM | 25 | -- | -- |
| 7.5 | SP | 33 | -- | -- |
| 9 | SP | 40 | -- | -- |
| 10.5 | SP | 33 | -- | -- |
| 12 | SP | 18 | -- | -- |
| 13.5 | CI | 2 | -- | 21 |
| 15 | CI | -- | 22 | 22 |

## 3 Results

### 3.1 Analytical results of adhesion factor using various methods

The adhesion factor of clay located at 13 m depth estimated by different empirical approaches are given in Table 4. The adhesion factors suggested by different authors are in range of 0.27 to 1.16. As various parameters are taken into consideration while estimating adhesion factor, differences in suggested values of α is also high. The adhesion factor for other layers are ignored as the remaining layers are granular soils (non-cohesive soils) for which the skin friction capacity of pile is calculated by the effective stress approach as specified by IS 2911 Section 1.

On the other hand, the skin friction of the soil sample is interpreted from load displacement curve of the plate load test as per the IS 2911 code (Fig. 3). Furthermore, skin friction is calculated as per adhesion factor (Table 4) and the values of it are presented in Fig. 4. The load capacity of pile predicted using the empirical equations is overestimated when compared to the skin friction obtained from pile load test.

**Table 4.** Adhesion factor estimated by various methods for Paradip soil

| Depth | Adhesion factor, α | | | | |
|---|---|---|---|---|---|
| | API (1984) | Sladen (1992) | Karlsud (2005) | Kulhaway and Jackson (1989) | Kolk and vander Velde (1996) |
| 0 m - 2 m | -- | -- | -- | -- | -- |
| 2 m - 13 m | -- | -- | -- | -- | -- |
| 13 m - 18 m | 1 | 1.16 | 1 | 0.27 | 0.52 |
| 18 m - 27 m | -- | -- | -- | -- | -- |

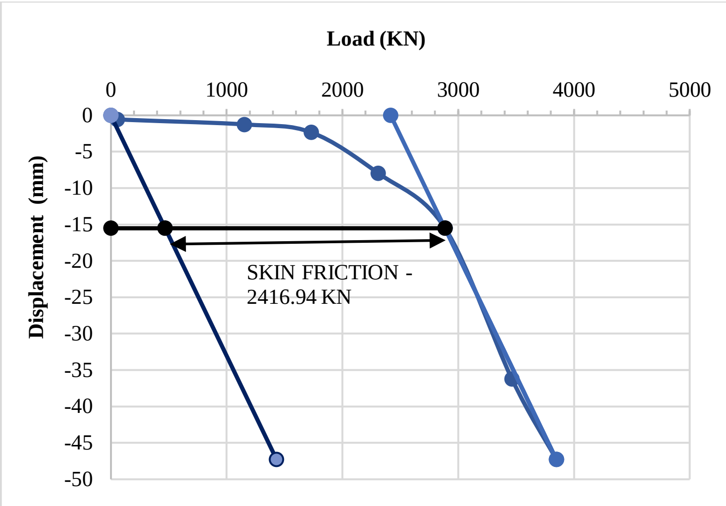


**Fig. 3**. Interpretation of skin friction as per IS method for Paradip Soil

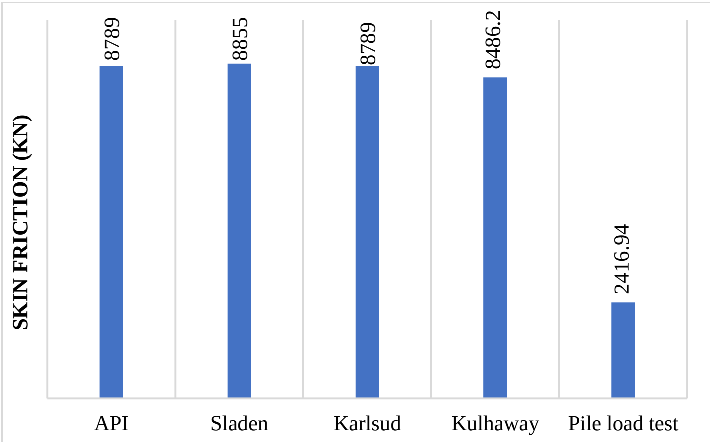


**Fig. 4**. Skin friction as per the adhesion factor suggested by different authors

### 3.2 Results of Numerical Analysis

In addition to estimation of skin friction capacity, the load displacement curve is predicted using PLAXIS-3D for static axial load applied on the top of pile. The variation in the load displacement curve obtained for $R_{inter}$ (adhesion factor) suggested by different authors and field load displacement curve is plotted in the Fig. 5.

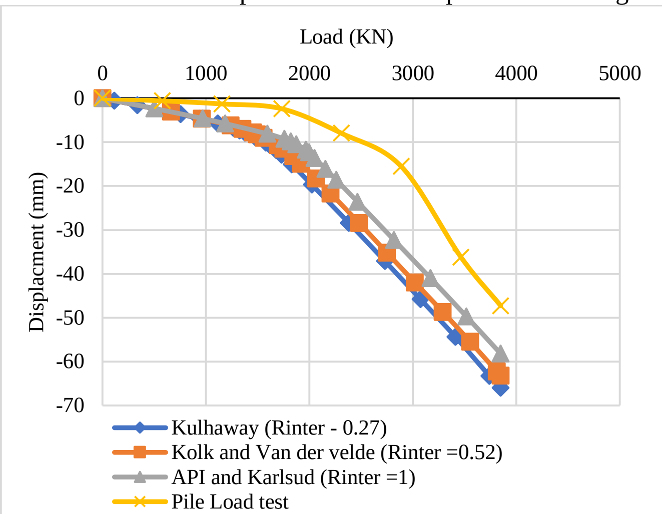


**Fig. 5. The load displacement curve obtained from numerical modeling and pile load test**

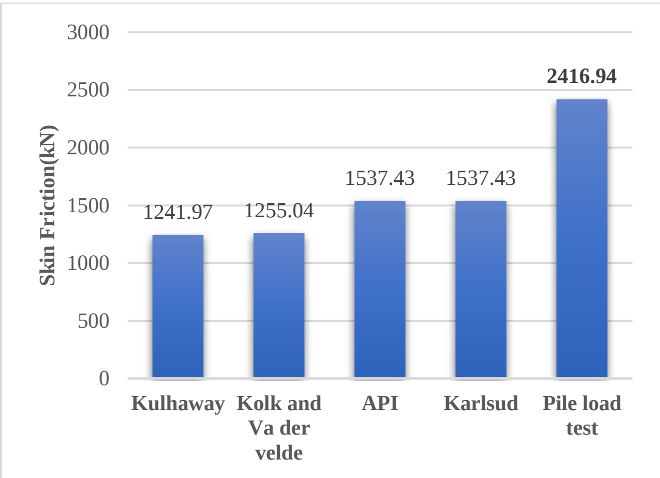


**Fig 6. The skin friction capacity from load displacement curves obtained from numerical modelling as per IS 2911 code**

As the $R_{inter}$ is increased to 1, the load displacement curve is also approached towards the field load displacement curve. The skin friction for the load displacement curve calculated as per IS code 2911 is shown in Fig. 6. The variation in skin friction capacities is very low as adhesion factor of clay is changed and also the skin friction of pile obtained by numerical model by varying the adhesion factor is underestimated wile compared to that obtained from plate load test. The skin friction calculated as per adhesion factor values suggested by API and Karlsud are close to that of Field load test. So, the adhesion factor estimated by API and Karlsud as 1 can be used for the clayey soil in Paradip situated at a depth of 13.5 m. The settlement of pile in the soil body were comparatively high with those of field settlements as shown in Fig 7.

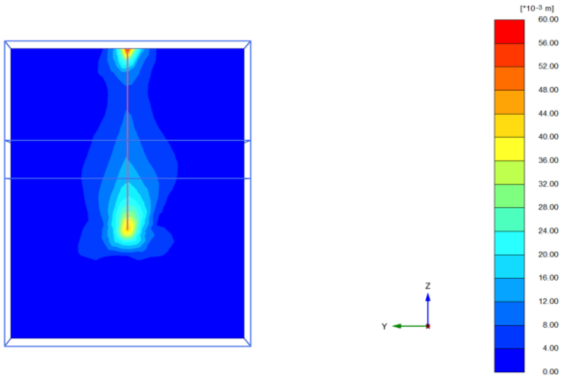


**Fig 7. The contour of settlement of pile in soil strata**

## 4 Conclusions

Based on the numerical studies and analysis of experimental data, arrived at the following conclusions given below:

- The variation in skin friction capacity is noticed to be very low with the change in the adhesion factor values.
- Settlements obtained by the numerical analysis are high when compared with that of field data.
- It is found that the load settlement curve obtained when adhesion factor of soft clay of unity is close to that of the field load settlement curve.
- Adhesion factors estimated by empirical methods are excessively simplified and cannot validate the reason for the change in adhesion factor for all kinds of soils.
- It is necessary to check the wide range of experimental data to know the reason behind the change in adhesion factor for different soil types and its effect on the calculation of skin friction.
- The skin friction predicted by the numerical approach is lesser when compared with that of experimental test. This may account for the constant stiffness of soil assumed in model and stiffness does not as the soil undergoes settlement.

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