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# Evaluation of Initial Stiffnesses and Ultimate Resistances of Shaft and Base of a Pile from Initial Load Test

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**Abstract.** Pile foundation is often used to transfer heavy loads deep into the soil. Pile derives its resistance from both shaft and base in case of axial loading. The pile-soil response is nonlinear and difficult to predict. Pile load tests are conducted on test piles and the load-displacement response obtained is used to validate or modify the design. This study proposes a simple method to estimate the initial stiffnesses and the ultimate resistances of the shaft and the base of a pile from initial pile load test results assuming non-linear hyperbolic responses of shaft and base. This new method would help designers to validate the design correlations and predict the pile responses better.

**Keywords:** Pile-Soil Response, Load-Displacement Curve, Nonlinear, Initial Pile Load Test.

## 1 Introduction

Due to rapid development in construction industry and speedy urbanization, high-rise buildings and heavy bridges that carry heavy loads require pile foundations that transfer these loads to deeper competent layers for stability and serviceability. Pile derives resistance through its shaft and base in case of axial loading. Piles are classified as end-bearing piles, friction piles or combination of end-bearing-friction piles based on the relative magnitude of shaft and base resistances.

Piling system is chosen considering ground conditions, characteristics of load, total and differential settlements and additional requirements of project. The ultimate capacity of the pile is estimated considering the strengths and unit weights of soil layers with depth, overburden pressure and other relevant parameters. The estimated capacities always need to be validated by conducting initial maintained load test. The estimated capacity may differ with the actual at site since the values of strength, stiffness, interface resistance between pile and soil, lateral earth pressure coefficient, etc. vary with depth and soil stratification and can be at variance from the design parameters considered for estimating the ultimate capacity of pile. The estimation of axial capacity of piles involves considerable uncertainties in selection of appropriate design parameters and the design rules are not always consistent with the installation procedures/processes involved.

As per IS 2911 – Part 4 [4], the ultimate and safe load on a pile are to be estimated by performing Pile Load Test (PLT). Initial pile load test is conducted on a “test pile” up to its failure or at least two and half times the design load to determine the ultimate and safe load with applied factor of safety.

Chin [3] developed a simple procedure to estimate the ultimate load capacity and initial stiffness of a pile from the load – displacement curve. Based on linear relationships between base load and settlement, Poulos [7] presented an approach for the prediction of load – displacement behavior of single pile and piers until failure. Meyerhof [6] examined the ultimate load of pile groups and the settlement of pile foundations in cohesive and non-cohesive soils. Armaleh and Desai [1] developed a method for estimating pile response using one dimensional finite element model for simulating non-linear point resistance response. Based on fifty instrumented loading tests, new load- transfer curves were developed by Bohn [2], for different types of piles and ground types without the need of conducting pressure meter tests. Madhav and Vijay [5] proposed a new analytical solution to estimate the non-linear responses of shaft and base of a pile using hyperbolic relationships.

## 2 Statement of the Problem

Estimating ultimate resistances and initial stiffnesses of shaft and base of pile using load - displacement curve from initial pile load test is important, as it enables verification of the a-priori predictions based on geometry of pile (i.e., diameter, length, and shape), method and mode of construction and other uncertainties involved during pile installation at the site. The present study determines first the ultimate, $P_{ult}$, and initial stiffness modulus, $k_p$, of pile from initial pile load test data. The ultimate resistances of shaft, $\tau_{max}$, and base, $q_u$, and the initial stiffnesses of shaft, $k_\tau$, and base, $k_b$, of a pile under suitable combination of loads are then estimated. The load (L) – displacement ($\delta$) data using estimated pile responses ($k_\tau$, $\tau_{max}$, $k_b$ and $q_u$) is predicted and compared with the real test data for validation.

## 3 Methodology

A single pile of diameter, d, length, L and with an axial load, P, considered is shown in Fig 1. The pile-soil system is modeled as Winkler type model with distinct non-linear responses for the base and shaft-soil resistances.

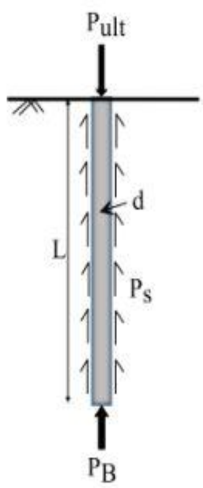



**Fig. 1.** Definition Sketch

A single rigid pile subjected to vertical loading derives its resistance by base and shaft resistances. The idealized representation of pile load test results of a single rigid pile, shaft and base resistances are shown in Figs. 2, 3 and 4 respectively. The initial slopes of the curves in Figs. 2, 3 and 4 represent the initial stiffness moduli of pile, $k_p$, shaft stiffness, $k_\tau$, and base stiffness, $k_b$, respectively. $P_u$ is the ultimate load on the pile, while $q_u$ and $\tau_{max}$ are the ultimate base and shaft resistances respectively.

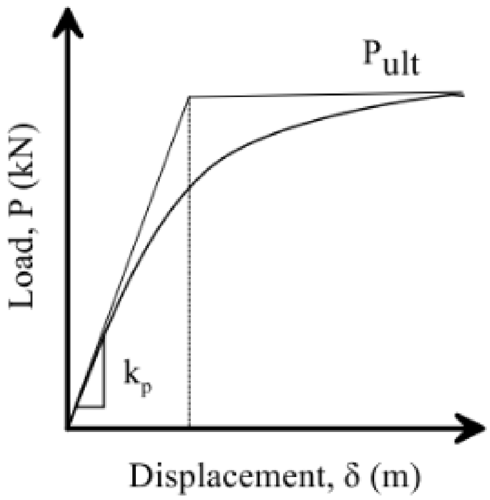



**Fig. 2.** Typical Pile Load vs Displacement Response

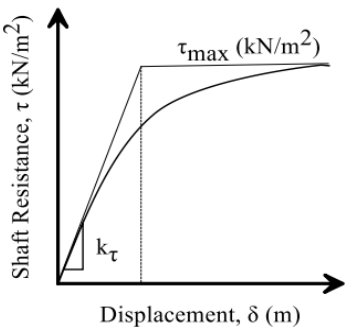



**Fig. 3.** Assumed Shaft Resistance, τ vs Displacement, δ

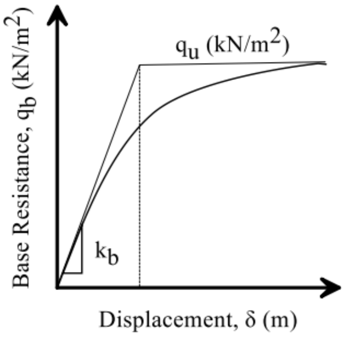



**Fig. 4.** Assumed Base Resistance, $q_b$ vs Dis placement, δ

The ultimate capacity, $P_u$, and initial stiffness, $k_p$, of the pile are the two key known parameters required to estimate the four parameters, $k_\tau$, $\tau_{max}$, $k_b$ and $q_u$ of the base and shaft responses. Chin's [3] method based on hyperbolic response between load and displacement is adopted to estimate $P_u$ and $k_p$. The load – displacement curve from initial pile load test is shown in Fig 5.

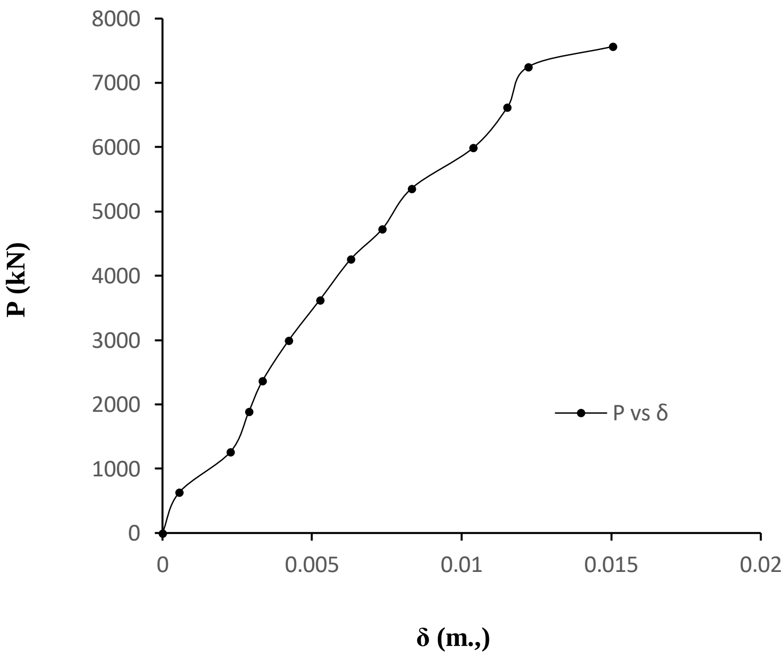



**Fig. 5.** Load vs Displacement Curve from Initial PLT

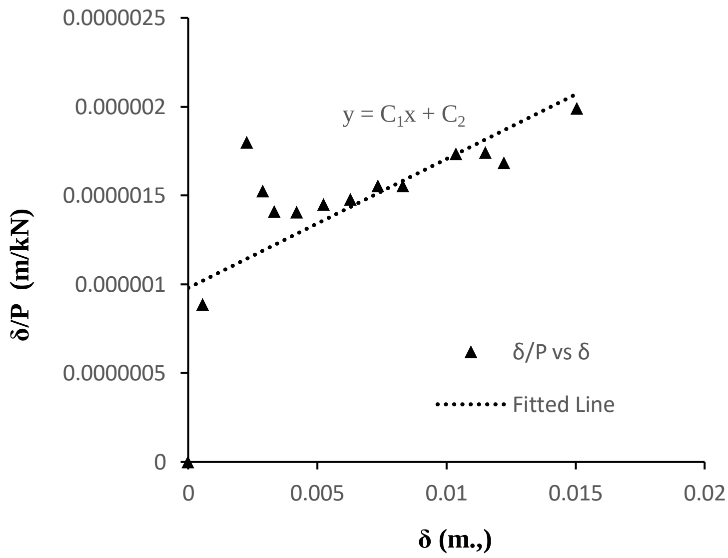



**Fig. 6.** Chin's Method for Estimation of $P_u$ and $k_p$

The ratio δ/P is plotted with δ is shown in Fig 6, and an equation

$$\delta/P = C_1\,\delta + C_2. \tag{1}$$

is fitted where intercept $C_1 = 1/P_u$ and the slope $C_2 = 1/k_p$.

A set of non-linear coupled equations derived by Madhav and Vijay [5] are given below:

1) Equation for $k_b$:

$$k_b = k_p^* - (4L/d)\,k_\tau \tag{2}$$

2) Equation for $k_\tau$:

$$k_\tau = (C_4 d_1 - C_2 d_2) / (C_1 C_4 - C_2 C_3) \tag{3}$$

3) Equation for $q_u$:

$$q_u = P_u^* - (4L/d)\,\tau_{max} \tag{4}$$

4) Equation for $\tau_{max}$:

$$\tau_{max} = \frac{\{P_2^*.\, A_2 - [(k_p^*/\, k_\tau) - (4.L/d)].\, P_u^*.\, k_\tau.\, \delta_2\}}{\{(4.L/d).\, [A_2 - k_p^*.\, \delta_2 + (4.L.\, k_\tau.\, \delta_2/d)]\}} \tag{5}$$

Where $k_p^* = k_p / (\pi d^2/4)$ - normalized stiffness of the pile, $k_\tau$ and $k_b$ are shaft and base stiffnesses respectively. $P_u^* = P_u / (\pi d^2/4)$ - normalized $P_u$ of the pile, $\tau_{max}$ and $q_u$ are maximum shaft and base resistances respectively.

$d_1$, $d_2$, $A_1$, $A_2$, $C_1$, $C_2$, $C_3$, $C_4$ are parameters used in equations as

$$d_1 = (P_1^*/\, \delta_1) - [(k_p^*.P_u^*)/A_1] \tag{6}$$

$$d_2 = (P_2^*/\, \delta_2) - [(k_p^*.P_u^*)/A_2] \tag{7}$$

$$A_1 = [P_u^* - (4.L.\, \tau_{max} / d)] + [k_p^* - (4.L.\, k_\tau)/d].\delta_1 \tag{8}$$

$$A_2 = [P_u^* - (4.L.\, \tau_{max} / d)] + [k_p^* - (4.L.\, k_\tau)/d].\delta_2 \tag{9}$$

$$C_1 = (4.L/d).\{(\tau_{max} / \tau_{max} + k_\tau.\, \delta_1) - (P_u^* / A_1) + (4.L.\, \tau_{max} / d.\, A_1)\} \tag{10}$$

$$C_2 = - (4.L.k_p^* / d.A_1) \quad (11)$$

$$C_3 = (4.L/d).\{(\tau_{max} / \tau_{max} + k_{\tau}.\ \delta_2) – (P_u^* / A_2) + (4.L.\ \tau_{max} / d.\ A_2)\} \quad (12)$$

$$C_4 = - (4.L.k_p^* / d.A_2) \quad (13)$$

The above equations were derived for 1/3rd and 2/3rd of $P_u$. However, some of the load tests are not carried out to a significant load but are limited to a small fraction of the ultimate load. Hence new sets of equations are derived for lesser load combinations, viz.,

Case 1: $P_1$= 0.3*$P_u$ and $P_2$= 0.6*$P_u$

Case 2: $P_1$= 0.3*$P_u$ and $P_2$= 0.5*$P_u$

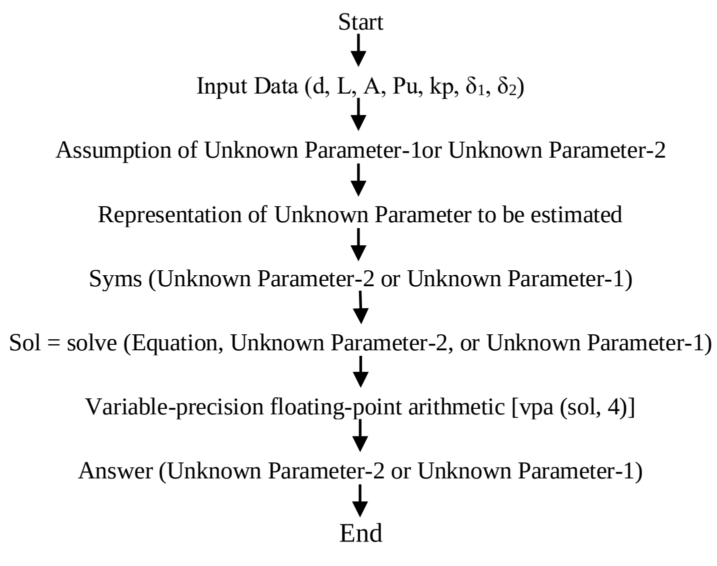
Case 3: $P_1$= 0.25*$P_u$ and $P_2$= 0.5*$P_u$

Case 4: $P_1$= 0.25*$P_u$ and $P_2$= 0.3*$P_u$

Pile parameters are estimated by substituting appropriate load combinations of $P_1$ and $P_2$ in Eqs. 2 to 5.

## 4 MATLAB Analysis

MATLAB is used to simplify the process of solving coupled second degree polynomial equations, having two unknown parameters.

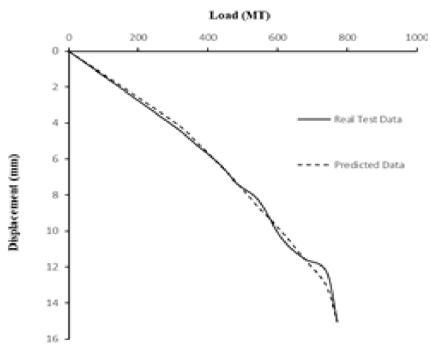



The four unknown parameters, $k_{\tau}$, $\tau_{max}$, $k_b$ and $q_u$ denoted as 1, 2, 3 and 4 respectively are estimated using four non-linear coupled equations. The above flowchart depicts the procedure followed in MATLAB software.

The procedure must be repeated for different assumed values of unknown parameter-1 to get corresponding unknown parameter-2. A set of values of $\tau_{max}$ are estimated using Equation 5 assuming $k_\tau$. Similarly, another set of $k_\tau$ are estimated using Equation 3 assuming $\tau_{max}$. $\tau_{max}$ was plotted against $k_\tau$, obtained from the above two procedures and the intersection of the two curves gives the $\tau_{max}$ and $k_\tau$ values for the pile under consideration. $\tau_{max}$ and $k_\tau$ are substituted in Equations 2 and 4 to obtain the values of $k_b$ and $q_u$ respectively.

## 5 Application of the Proposed Method

The present method is applied to 6 test piles for which the load-displacement curves from initial loading tests are available. The ultimate resistance and stiffness modulus of each test pile are determined using Chin's [3] method. The four unknown parameters of each pile ($k_\tau$, $\tau_{max}$, $k_b$, and $q_u$) are estimated using appropriate load combination (Case 1, Case 2, Case 3, or Case 4). Load-displacement curves of 6 test piles considered in this study are shown in Fig 7 to 12. The diameter and length of all 6 piles are 1.0 m., and 24.0 m., respectively.

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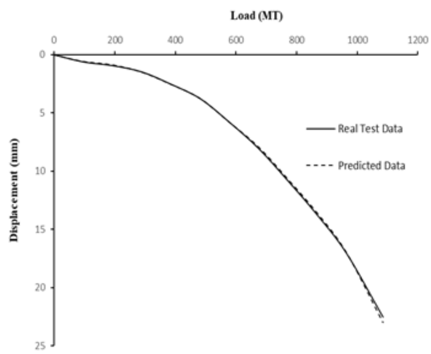


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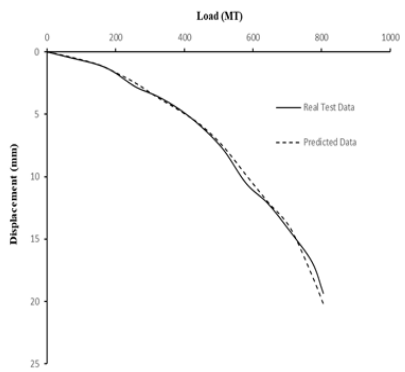


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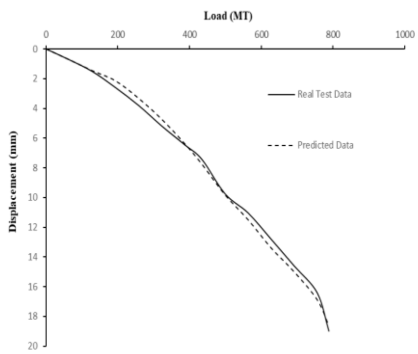


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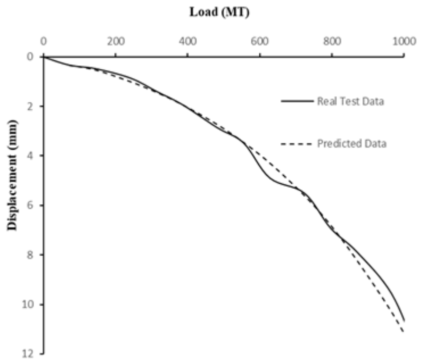


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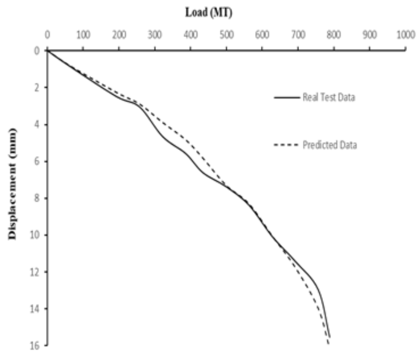


(12)

**Fig. 7 – 12.** Measured and Predicted Load-Displacement Curves of a pile located at Bur balasan, Dharaikuri, Karala, Kartowa, Mahananda and Talma

The ultimate load, $P_u$, and the initial stiffness, $k_p$, are listed in Table 1. The load combinations used for these test piles are given in Table 2.

**Table 1.** Ultimate Load and Initial Stiffness

| Pile Reference | $P_u$ (MN) | $k_p$ (MN/m) |
|---|---|---|
| Buribalasan, W. B | 20.0 | 1,666.7 |
| Dharaikuri, W. B | 16.7 | 3,333.3 |
| Karala, W. B | 12.5 | 2,500.0 |
| Kartowa, W. B | 20.0 | 1,428.6 |
| Mahananda, W. B | 16.7 | 3,333.3 |
| Talma, W. B | 20.0 | 1,666.7 |

**Table 2** Load Combinations for Piles

| Pile Reference | $P_1$ | $P_2$ |
|---|---|---|
| Buribalasan, W. B | $0.25*P_u$ | $0.3*P_u$ |
| Dharaikuri, W. B | $0.3*P_u$ | $0.6*P_u$ |
| Karala, W. B | $0.25*P_u$ | $0.3*P_u$ |
| Kartowa, W. B | $0.3*P_u$ | $0.6*P_u$ |
| Mahananda, W. B | $0.3*P_u$ | $0.6*P_u$ |
| Talma, W. B | $0.25*P_u$ | $0.3*P_u$ |

*Note: Load combination is selected based on available initial load test data.

The estimated parameters of each pile obtained from the analysis are summarized in Table 3.

**Table 3** Estimated Initial Stiffnesses and Ultimate Resistances of Shaft and Base

| Pile Reference | $k_\tau$ (MN/m$^2$/m) | $\tau_{max}$ (kPa) | $k_b$ (MN/m$^2$/m) | $q_u$ (MPa) |
|---|---|---|---|---|
| Buribalasan, W. B | 14 | 20 | 778 | 23.5 |
| Dharaikuri, W. B | 34 | 38 | 980 | 17.6 |
| Karala, W. B | 26 | 40 | 687 | 12.1 |
| Kartowa, W. B | 14 | 30 | 474 | 22.6 |
| Mahananda, W. B | 26 | 35 | 1748 | 17.9 |
| Talma, W. B | 15 | 28 | 682 | 22.8 |

## 6 Results and Discussion

The main purpose of this study is to estimate the shaft and base resistance parameters of pile i.e., $k_\tau$, $\tau_{max}$, $k_b$, and $q_u$ using load – displacement data from initial pile load test. The estimated shaft and base resistances of piles obtained for the first time using this method are presented in Table 3.

## 7 Conclusions

This paper presents a simple method to estimate the ultimate resistances and initial stiffnesses of shaft and base, based on the analysis of initial pile load test data. A set of equations for different load combinations are developed for the purpose of determining initial shaft and base stiffnesses and ultimate shaft and base resistances. The proposed method is applied to six pile load test data using suitable load combination. The estimated responses of pile are used to predict the load – displacement responses which compare closely with the measured ones.

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