

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Analysis of pile load-settlement data

Analyse des données de charge-règlement de pile

D.M. Dewaikar

Professor, Department of Civil Engineering, Indian Institute of Technology Bombay,

ABSTRACT

Several methods are available for the estimation of ultimate pile capacity from the load-settlement data of a pile. In some cases, it is difficult and also time consuming to conduct the pile load test up to failure (especially for rock socketed piles). Therefore, for the estimation of pile capacity, load-settlement data collected from the field is required to be extrapolated. This paper presents a method of extrapolation to predict the complete load-settlement behavior of a pile upto failure so as to estimate its ultimate capacity. Gregory Newton interpolation formula and difference table are used for the extrapolation purpose. Forty cases of rock socketed pile load-settlement data are analyzed with the proposed extrapolation method. From the estimated ultimate load, the allowable load is computed as per IS 14593 (1998) and compared with the adopted design load. The extrapolated load-settlement curves show a fairly good comparison with the field data.

RÉSUMÉ

Plusieurs méthodes permettent de déterminer la charge limite de pieux à partir de la courbe de charge vs déplacement. Cependant, effectuer un essai de chargement sur pieu jusqu'à rupture peut être difficile et long, particulièrement pour des pieux fondés dans la roche. Pour estimer la charge limite d'un pieu il faudrait donc pouvoir extrapoler la courbe charge/déplacement obtenue d'essai sur site. Cet article présente une méthode d'extrapolation de la courbe charge/déplacement d'un pieu jusqu'à la rupture, afin de déterminer la charge limite du pieu. Les formules d'interpolation et table de différentiation de Gregory-Newton sont utilisées aux fins d'extrapolation. Les données de tassement sous charge de quarante pieux ancrés dans la roche ont été analysées selon la méthode d'extrapolation proposée. Pour chaque charge limite estimée la charge admissible a été calculée selon IS-14593 (1998) et comparée avec la charge de conception. Une bonne concordance entre les prédictions charge/déplacement par extrapolation et les résultats d'essai sur site a été trouvée.

Keywords : ultimate load, safe load, extrapolation, ordinary difference table, Gregory-Newton interpolation, load-settlement curve

1 INTRODUCTION

Field load tests are conducted to ascertain field performance of a pile and for the estimation of its ultimate capacity. Since pile load tests cannot be conducted upto failure, especially for rock socketed piles, this necessitates the use of numerical/empirical methods for predicting load settlement behavior and ultimate loads. This paper describes the details of a numerical method for the extrapolation of field load tests data and these extrapolated data are used to estimate ultimate pile capacity using available methods of estimation of ultimate load. From the estimated ultimate load, the allowable load is computed as per IS 14593 (1998) and compared with the adopted design load.

2 FIELD LOAD TESTS

During the last decade, bored cast in situ rock socketed piles are commonly being used all over the Mumbai region. As per contract condition, pile load tests are conducted for every site as per guidelines given in IS 2911 (1985). Each site involves two types of load tests, namely initial pile load test and routine pile load test. Initial pile load tests are performed to determine ultimate pile load. Such tests, performed on the test pile involve maximum loads equivalent to 2.5 times the design load. The routine load tests are carried out on the working piles subjected to a maximum test load of 1.5 times the estimated design load.

Total forty pile load test data are collected from various places of Mumbai region for the present analysis.

3 METHOD OF EXTRAPOLATION

Following steps are followed in the proposed method of extrapolation.

- 3.1 Plot of load vs. settlement data (load along x-axis and settlement along downward y axis)
- 3.2 Choosing some discrete evenly spaced points (evenly spaced points along load axis and corresponding settlements) from the load-settlement curve
- 3.3 The purpose of choosing evenly spaced points is nothing but using Gregory-Newton interpolation formula for extrapolation purpose
- 3.4 Development of an ordinary difference table

Here one example of ordinary difference table is shown in Table 1.

With the help of the modified data (i.e. evenly spaced data points chosen from load-settlement curve) the above ordinary difference table is obtained. The advantage of this difference Table is that, it is possible to depict the nature of curve or the degree of a polynomial. In the column of the difference table where all the difference become constant the order of difference

Table 1: General form of ordinary difference table

| x_i | f_i | $df[x_i]$ | $d^2f[x_i]$ | $d^3f[x_i]$ | $d^4f[x_i]$ |
|-------|-------|-----------|-------------|-------------|-------------|
| x_0 | f_0 | $df[x_0]$ | $d^2f[x_0]$ | $d^3f[x_0]$ | $d^4f[x_0]$ |
| x_1 | f_1 | $df[x_1]$ | $d^2f[x_1]$ | $d^3f[x_1]$ | |
| x_2 | f_2 | $df[x_2]$ | $d^2f[x_2]$ | | |
| x_3 | f_3 | $df[x_3]$ | | | |
| x_4 | f_4 | | | | |

Where, x_i = pile load (chosen evenly spaced point from load settlement curve) in Tons

f_i = settlement in mm corresponding to pile load, x_i
 $df[x_i]$ = first order difference = $f_{i+1} - f_i$
 $d^2f[x_i]$ = second order difference = $d^2f[x_{i+1}] - d^2f[x_i]$
 $d^n f[x_i] = n^{\text{th}}$ order difference = $d^n f[x_{i+1}] - d^n f[x_i]$
 $d^n f[x_i] = n^{\text{th}}$ order difference = $d^n f[x_{i+1}] - d^n f[x_i]$
 n = order of difference
 $i = 0$ to number of data points
 (eg. here number of data points = 4)

With the help of the modified data (i.e. evenly spaced data points chosen from load-settlement curve) the above ordinary difference table is obtained. The advantage of this difference Table is that, it is possible to depict the nature of curve or the degree of a polynomial. In the column of the difference table where all the difference become constant the order of difference indicates degree of the polynomial.

3.5 Development of polynomial equation for extrapolation

Polynomial for extrapolation is derived with the help of Gregory-Newton interpolation formula and the ordinary difference table obtained in the previous step.

The general form of Gregory-Newton interpolation formula is shown in Eq. 1

$$f(x) = f_0 + \frac{(x-x_0)}{h} df(x_0) + \frac{(x-x_0)(x-x_0-h)}{2!h^2} d^2f(x_0) + \frac{(x-x_0)(x-x_0-h)(x-x_0-2h)}{3!h^3} d^3f(x_0) + \frac{(x-x_0)(x-x_0-h)(x-x_0-2h)(x-x_0-3h)}{4!h^4} d^4f(x_0) \quad (1)$$

where, x = any load point at which, settlement, $f(x)$ is to be calculated
 h = common difference between two consecutive x values

3.6 Plot of extrapolated load-settlement curve

Data are extrapolated using the polynomial equation as Shown in previous step and using these extrapolated data load-settlement curves are generated as shown in Fig.1 for one of the test piles.

4 ESTIMATION OF ULTIMATE LOAD

There are several methods available for estimation of ultimate pile capacity from the load settlement data, such as, Van der Veen method (1953), Brinch Hansen's method (1963), De Beer's method (1968), Chin's method (1970) etc. For the present analysis, De Beer's method is used to estimate ultimate pile capacity.

4.1 De Beer's yield load (1968)

De Beer made use of the logarithmic linearity by plotting the load-settlement data in a double-logarithmic diagram. The ordinate of intersection point of the two straight portions of the curve gives the magnitude of ultimate load as shown in Fig.2.

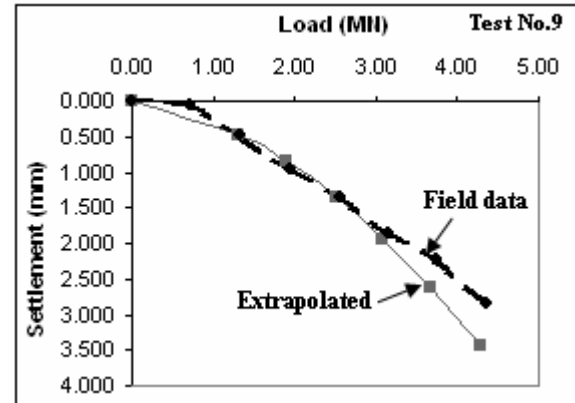


Fig.1: Load-settlement curve

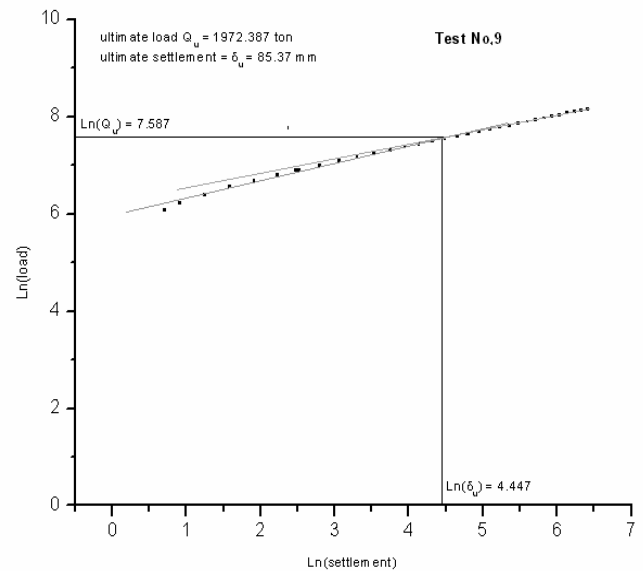


Fig.2: Ultimate load by De Beer's method

5 SAFE LOAD CRITERIA

As per IS 14593 (1998), the safe load for a rock socketed pile is the minimum of the following.

- 50% of load at 12mm settlement
- $1/3^{\text{rd}}$ of the ultimate failure load

6 RESULTS AND DISCUSSIONS

The pile load test data are extrapolated using the method described above and after that, De Beer's (1968) method is applied to the extrapolated data to estimate the ultimate pile capacity and the corresponding settlement. Safe loads are computed applying IS code criteria and reported in Table 2.

- Safe loads and adopted design loads are compared and percentage deviations are evaluated. The deviation ranges within $\pm 20\%$ in 33 cases and among them in 26 cases, the percentage deviation is

near about $\pm 10\%$, as shown in Table 2. Similarly, there is a reasonably good match between the field load-settlement curves and extrapolated curves (Fig.1).

- Factor of safety values are in the range of 3-3.75 in 70% cases (Table 2).

Table 2 : Results of the analysis

| Test No | Safe Load Tons | Design Load Tons | % Deviation | Factor of safety |
|---------|-------------------|---------------------|----------------|---------------------|
| 1 | 507.99975 | 495 | 2.626212 | 3.4 |
| 2 | 308.81475 | 315 | -1.96357 | 5 |
| 3 | 362.16225 | 365 | -0.77747 | 3.7 |
| 4 | 456.87525 | 515 | -11.2864 | 3.8 |
| 5 | 282.14775 | 200 | 41.07388 | 3.2 |
| 6 | 225.30975 | 188 | 19.84561 | 3.6 |
| 7 | 527.67975 | 525 | 0.510429 | 3.7 |
| 8 | 643.65525 | 595 | 8.177353 | 3.65 |
| 9 | 492.90825 | 453 | 8.809768 | 4 |
| 10 | 436.81725 | 475 | -8.03847 | 4.5 |
| 11 | 591.07275 | 565 | 4.614646 | 3.6 |
| 12 | 354.075 | 350 | 1.164286 | 3.6 |
| 13 | 372.3675 | 375 | -0.702 | 3.6 |
| 14 | 334.68975 | 330 | 1.421136 | 3.55 |
| 15 | 518.73233 | 480 | 8.069235 | 3 |
| 16 | 279.20025 | 200 | 39.60013 | 3.45 |
| 17 | 226.96425 | 186 | 22.02379 | 3.5 |
| 18 | 237.675 | 200 | 18.8375 | 4.3 |
| 19 | 210.855 | 200 | 5.4275 | 4.8 |
| 20 | 255.5797 | 275 | -7.06191 | 4 |
| 21 | 249.9816 | 300 | -16.6728 | 3 |
| 22 | 545.328 | 550 | -0.84945 | 3 |
| 23 | 339.7597 | 300 | 13.2533 | 5 |
| 24 | 183.3483 | 200 | -8.32584 | 3 |
| 25 | 124.51 | 215 | -42.0884 | 3 |
| 26 | 187.4266 | 175 | 7.10095 | 3 |
| 27 | 352.9702 | 350 | 0.84864 | 4.4 |
| 28 | 669.975 | 675 | -0.74444 | 3.2 |
| 29 | 687.724 | 720 | -4.48278 | 3 |
| 30 | 464.23367 | 439 | 5.74799 | 3 |
| 31 | 241.62525 | 240 | 0.67719 | 4.5 |
| 32 | 333.54975 | 300 | 11.1833 | 4.3 |
| 33 | 251.96025 | 250 | 0.7841 | 3.4 |
| 34 | 147.99975 | 215 | -31.1629 | 5.5 |
| 35 | 348.48975 | 560 | -37.7697 | 3.4 |
| 36 | 527.15025 | 475 | 10.979 | 3.6 |
| 37 | 555.02475 | 550 | 0.91359 | 3.1 |
| 38 | 108.56933 | 150 | -27.6204 | 3 |
| 39 | 164.46525 | 175 | -6.01986 | 3.6 |
| 40 | 208.125 | 200 | 4.0625 | 6.3 |

7 CONCLUSIONS

The extrapolated load-settlement curve shows a fairly good comparison with the field curve. Comparison between safe loads and adopted design loads also shows satisfactory results. Factors of safety values are in the range of 3 to 3.75 in 70% cases. This leads to the conclusion that, proposed method of extrapolation and estimation of ultimate pile capacity using De Beer's method are quite useful in cases where it is difficult to conduct pile load tests upto failure.

REFERENCES

- Chin F.K. 1970. Estimation of the Ultimate Load of Piles from Tests not carried to Failure, Proceedings of Second SE Asian Conference on Soil Engineering., Singapore, 11-15th June, pp. 81-92.
- De Beer, E.E. Proefondervindlijke Bijdrage Tot de Studie Van Het Grensdraag Vermogen Van Zand onder Funderingen Op Staal, Tijdschrift der Openbar Verken van België, No. 6, 1967, and Nos. 4-6, 1968.
- Gerald C.F. & Wheatley P.O. 1999. *Applied Numerical Analysis*, sixth edition, California Polytechnic State University, San Luis Obispo.
- Hansen J.B. 1963. Hyperbolic stress response, cohesive soils: Discussion, *Journal of SMFE Division*, ASCE, Vol.89, SM4, pp.241-242.
- Hurnbeck, R.W. 1975. *Numerical Analysis*, New York, Quantum Publication.
- IS: 2911 (Part 4) 1985. Code of practice for Design and Construction of Pile Foundation: Load tests on piles, (Reaffirmed 1995).
- IS: 14593 1998. Designs and Construction of Bored Cast –in-situ Piles Founded on Rocks- Guidelines.
- Van der Veen C. 1953. The bearing capacity of a pile, *3rd ICSMFE*, pp.84 – 90.