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LATERAL LOAD CAPACITY ESTIMATION OF LARGE DIAMETER BORED PILES AND ITS IMPLEMENTATION - A STUDY

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Summary

Bridge foundation, using large diameter bored piles are presently very common in India due to need of faster implementation, environmental hazard mitigations and also availability of modern equipments. Long span and continuous superstructures transmit large horizontal forces to the substructure and foundation system, under serviceability as well as accidental/occasional loading conditions. Adopting modern seismic dampners and transmission units one can limit or minimise to certain extent the transfer of lateral load on the foundation system. Even after the dampening, the residual horizontal force is often quite high, which needs to be resisted by the foundation system. Proper assessment of lateral capacity of piles is thus important to cater for horizontal forces, particularly in the design stage, to work out appropriate foundation for the structure.

Designed capacity of piles is dependent on many factors, some of which can be determined with reasonable accuracy and the assessment of others is difficult. Assessment of soil properties, which contributes largely towards the lateral load capacity of the piles, is quite



difficult. Further, the lateral load capacity of a group of piles depends on the permissible lateral movement of the pile at the pile cap level satisfying the serviceability requirements and design tolerances for the proposed structure. The embedded length of pile vis-à-vis its sectional properties plays a major role in deciding the behavioural pattern under lateral load. Long term behaviour of pile material and soil, the loading patterns on structure, scour of river, etc. also play important role in the lateral load carrying capacity of a pile. This paper discusses all these aspects.

Often lateral load capacity of a pile is decided based on the load test conducted on individual piles. The authors feel that deciding lateral load capacity for the design of a pile foundation, only on the basis of load tests, which indicates the capacity at the time of testing and very often do not depict the actual long term situation, is not desirable. A single pile which moves laterally during load testing does not provide a direct answer to the various other aspects controlling/affecting the lateral resistance both for single pile or a pile group.

The paper discusses the authors' approach to determine lateral load capacity in compatible with the provision of Indian Standards and applied in their recent projects in India.

1.0 INTRODUCTION

Use of bridge foundations with large diameter piles, whether in land or in rivers with low scour has become quite common in India. Bridge structure is subjected to reversible longitudinal & transverse horizontal forces, and, raker piles, commonly used till eighties, were adopted to take care of these lateral forces. Gradual change from use of smaller diameter driven piles to high capacity large diameter bored cast-in-situ piles, which are more environmental friendly during installation, and faster in implementation has onset a trend to provide vertical piles for resisting, both, vertical & horizontal loads. Accordingly the assessment of horizontal load capacity of pile in addition to vertical capacity has become an important issue in the design.

The ultimate resistance of a vertical pile to lateral load and the deflection of the pile as the load builds up to its ultimate value are complex matters involving the interaction between a structural element and the soil in which it is embedded. The structural elements as well as the soil deform partially elastically and partially plastically. Elastic behaviour of the soil is only an idealised assumption. The deflection pattern of a pile depends on its boundary condition particularly at top where it may be free to rotate or rigidly fixed to a pile cap or is free to rotate at top of soil level but is fixed at much higher level in a pile cap such as foundation in a scoured river.

In majority of cases in India, piles are embedded in soil and are non-socketed. The lateral capacity of these piles depends to a larger extent on the properties of soil. Piles with tips socketed in rock however, have a different approach wherein the socketed area and/or structural capacity of the pile governs the lateral capacity.

Till recent years, due to the very complexity involved in the determination of lateral load carrying capacity, the capacity of piles were being assumed as an adhoc percentage of the vertical load carrying capacity of piles without going in for any analytical estimate. Raker piles were extensively used to cater for high lateral loads. As explained by Chakrabarti A. design of foundation with raker piles in combination with vertical pile could be solution, when a major portion of the horizontal load acts in reversible manner if the lateral load



capacity of a pile is considered as an adhoc percentage of its vertical load. Further, installation of bored piles in a rake, calls for use of liner for the full length making it more difficult to implement.

2.0 FAILURE MECHANISM

2.1 Soil Behaviour : The soil closer to the top surface initially resists the lateral load on a vertical pile. At comparatively lower loads, the soil behaves elastically and also transfers pressure from the top to the deeper stratum. With increase in load the topsoil tends to become plastic and transfer more load to the lower depths. The behaviour of soil reaction again depends on the width to depth ratio of the pile and its restraint conditions at the top level.

2.2 Pile Movement/Rotation : A short rigid pile, unrestrained at the top with length/diameter ratio upto around 12, tends to rotate about a point slightly above the bottom tip and passive resistance develops in the portion below the point of rotation whereas the top is subjected to active pressure. However, the same pile with a rigid pilecap tends to deflect/shift laterally en mass and active resistance develops for the entire length.

The failure mechanism of a pile with longer length of embedment is different. The passive resistance of the lower part of the pile is infinite, thus rotation of the pile is difficult occur and it remains vertical. Only the top deflects either with uni-directional rotation like a cantilever for a free pile head and like a propped cantilever or both end fixed condition compatible with level of fixity.

2.3 Failure Criteria/Serviceability Criteria : The ultimate failure for a long pile occurs when the moment on the pile induces a plastic hinge. But this phenomenon occurs after a large lateral displacement as well as rotation (for free piles heads) have taken place. But in most of the cases such large movements of the foundation system creates serviceability problems for the bearing system as well as the superstructure. Thus the lateral load capacity of long piles are decided on the basis of limiting lateral deflection at the pile top.

3.0 LATERAL LOAD CAPACITY CALCULATION

3.1 Criterion : As stated earlier the criteria for deciding the lateral load capacity of a long pile under different soil condition, pile rigidity and fixed end conditions of the pile is the limit upto which lateral deflection of the pile at the ground surface/pilecap level (as the case may be) can be permitted. It is not to be the ultimate lateral load resistance of the pile, considering a total soil structure interaction between a semi rigid structure and non-homogenous, often non-elastic soil mass, before the pile is subjected to its ultimate moment capacity causing formation of a hinge in pile structure in the embedded portion.

3.2 Approaches of Analysis : Two approaches that have been professed by various authorities, although both of them have limitations, are :

- a) The elastic approach, where the soil is assumed as an ideal elastic continuum.
- b) The sub-grade reaction (winkler model) approach where the continuous nature of the soil medium is ignored and the pile reaction at a point is simply related to the corresponding deflection of the pile at that point.



Elastic Approach : The very important and fundamental aspect of the approach is that under pure elastic condition the horizontal displacement of soil (be it in the direction of applied load or in the opposite face) and the pile are equal. The elastic analysis thus assumes that the soil behind the pile adheres to the pile at all times which is basically not correct. The elastic approach also makes a definite distinction between socketed pile and non-socketed pile.

To consider soil as an elastic continuum is more satisfactory assumption as it accounts for the continuous nature of the soil. Perhaps this may be a more appropriate approach for mathematical representation when group action of piles are taken into account. But the near impossible and daunting task is to determine the elastic soil modulus, even for single layer. Whereas for long piles the soil affected is mostly layered. Thus this is not a common approach, though several authors have deliberated on this approach.

Subgrade Reaction Modulus Approach : This is a concept which was even conceived by Terzaghi. The approach characterizes the soil as a series of unconnected linearly elastic springs, so deformation occurs where only loading exist and interalia soil resistance is mobilised when deformation takes place. The obvious disadvantage of the approach is the basic assumption of lack of continuity in all direction whereas in real situation the soil is some what continuous. The elastic spring constant, commonly known as modulus of subgrade reaction, is dependent on the width of pile and often on the depth of the particular loaded area of the soil.

The Most Accepted Approach : The exact solution to the problem of a laterally loaded flexible or semi rigid pile in an elastoplastic soil mass is a complicated and difficult one in a multi dimensional continuum mechanism. As such it warrants the designer to adopt certain measures and assumption, which may tend to a trifle adhocism. However considering all factors the method of subgrade modulus reaction is the most acceptable practice as it provides a relatively simple means of analysis and enables factors such as non linearty, variation of soil stiffness with depth, layering of soil profile etc. to be taken into consideration.

Comparison of displacement and rotation factors for long piles by adopting the elastic method and those determined by subgrade modulus method have shown higher values by the later method. As such it is felt that adopting the subgrade modulus method, even if it gives conservative values, the pile lateral load capacity calculation is on the safer side for the structure.

4.0 CALCULATING RESISTANCE TO LATERAL LOAD

4.1 Uncertain factors : Although the modulus of subgrade reaction approach has been extensively studied but the research has not yielded any simple design method which can easily and universally adopted to any soil or type of pile. There are many inter-related factors and a few dominant factors include –

- a) The pile length and its stiffness alongwith the soil parameters decides the failure mechanism i.e. whether the entire pile will rotate for deflection or the major part of the embedded length will remain vertical.
- b) The type of loading, whether sustained or alternating or pulsating or accidental and their influences & the degree of yielding of the soil.
- c) Scouring of soil mass around the pile of the pile group, particularly for river bridges in alluvium deposits.



d) Seasonal shrinkage of clayey soil away from the upper part of the pile shaft etc.

4.2 Need for Simplification : After detailed deliberations most of the researchers/authors have suggested only simplified procedures as elaborate calculation processes are not justified, because of the non-homogeneity of the natural soil deposits and the disturbance to the soil caused by pile installation. None of these factors, though very significant, can be reproduced in the calculation method. Various simplifications have been necessary in order to provide solutions to this complex problem of soil structure interaction. The Bureau of Indian Standards (BIS) has, after reasonable studies, suggested certain simplified methods as detailed later. The authors have used these simplified methods and guidelines of BIS for load testing and its acceptance criteria to decide the theoretical safe lateral load capacity of vertical piles for permissible deflection.

4.3 Assessment of Modulus of Sub-grade Reaction : The modulus can be determined by :

- a) Full scale lateral load test on a pile
- b) Plate load test
- c) Empirical correlation with other soil properties

The method at (a) has been used by several researches e.g. Matlock & Ripperberge, Reese & Cox etc. but they are time consuming, requires care and are very expensive. The method is also prone to give wrong values due to inadequacy in instrumentation.

The pioneers in the field like Terzaglu, Broms etc. have discussed method (b) in detail but ultimately attempts have been made by them to co-relate these results with the other elastic parameter and properties of the soil.

Ultimately most of the researcher in this field has tried to co-relate the basic nature and property of the soil to an empirical value of the subgrade reaction. BIS has specified certain values to be adopted which have been discussed later.

4.4 Group Effect & Repeated Loading : It has been often emphasized that for vertical capacity of a pile group, the group action plays a major part. The authors while working on the lateral load capacity of a pile foundation system based on the capacity of a single pile have been often advised that the method adopted is quite conservative as pile in a group will have larger capacity. However Davisson (1970) states that the spacing of piles in the direction of the load is of high importance. No positive decision in this respect can be taken to have rectangular grids in Indian condition mainly, due to seismic load (which constitutes major part of lateral load) and can act in any direction. There are various theories on the group effect of piles based on loading but the ideal spacing of $8d$ in the direction of the load as suggested by a few researchers is highly impractical.

Similarly, repetition of loading has its effect on the soil structure interaction and on the lateral load carrying capacity but again for bridge structures the lateral loads, which are the major contributors are neither pulsating nor very frequent.

4.5 Effect of Consolidation and Creep : As a result of consolidation and creep of the soil surrounding a laterally loaded pile, considering the elasto plastic nature of soil, an increase in lateral deflection and a re-distribution of soil reaction will occur each time. Though for fully



granular and non-cohesive soil the value effective subgrade modulus (k) equals to the test results but with cohesive soil the relation of the former to later is always less than unity.

Due to long term effect of repetitive loading, consolidation and creep, it is desirable not to design a pile foundation on the basis of load test only. These results may only be used as a confirmatory data to the theoretical safe capacity, as adopted in design.

4.6 Effect of Scour and Future Construction : For the design of pile foundation of a bridge structure it is necessary that the depth of design scour level ($2d$ for piers and $1.27d$ for abutments) are determined and the scoured condition is assessed for determination of the capacity of the pile. It is almost impossible to simulate a deep scour condition for a pile load test with facilities for adequate deflection and rotation of a free standing pile upto its top.

Further for flyovers in land where there are possibility to construct an underpass/subway adjacent to foundations in the near future, the pile capacity should take into account such provisions.

5.0 METHOD ADOPTED BY THE AUTHORS

5.1 Provisions in BIS Code to Determine the Lateral Deflection: The BIS Code stipulates the followings for determination of lateral deflection at the pile head and the depth of fixity.

5.1.1 The long flexible pile, fully or partially embedded, is treated as a cantilever fixed at depth below the ground level (see Fig. 1)

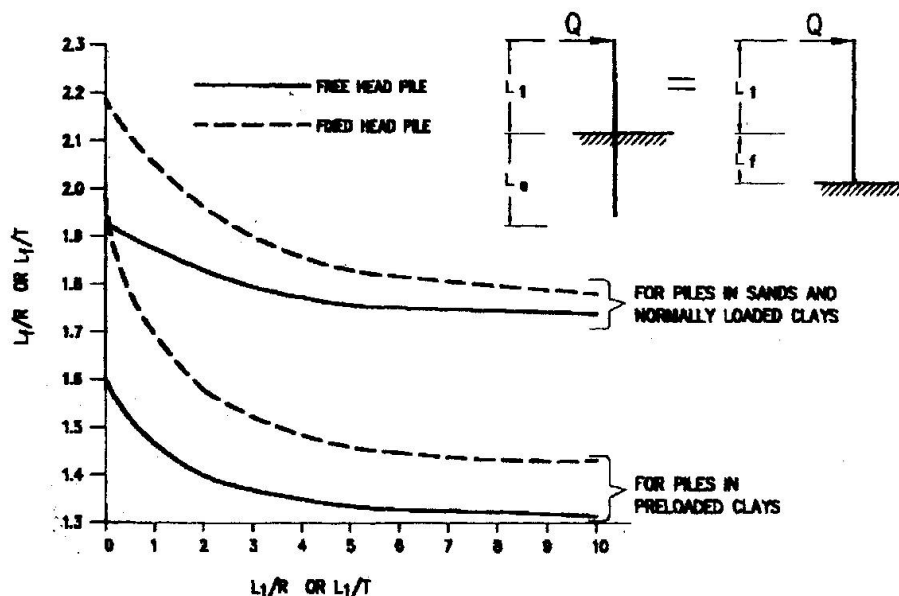


FIG. 1 : DETERMINATION OF DEPTH FIXITY

5.1.2 The depth of fixity and hence the equivalent length of the cantilever are determined using the plots given in Fig. 1



Where $T = 5 \sqrt{EI/K1}$ and $R = 4 \sqrt{EI/K2}$

(K1 and K2 are constants given in Table 1 and 2 below.

E is the Young's modulus of the pile material in kg/cm^2 and I is the moment of inertia of the pile cross-section in cm^4)

TABLE 1 : VALUES OF CONSTANT K1 (kg/cm^3)

| TYPE OF SOIL | VALUE | |
|--|-------|-----------|
| | Dry | Submerged |
| Loose Sand | 0.260 | 0.146 |
| Medium Sand | 0.775 | 0.525 |
| Dense Sand | 2.075 | 1.245 |
| Very loose sand under Repeated loading or Normally loading clays | --- | 0.040 |

TABLE 2 : VALUES OF CONSTANT K2 (kg/cm^3)

| UNCONFINED COMPRESSIVE STRENGTH IN kg/cm^2 | VALUE |
|---|--------|
| 0.2 to 0.4 | 7.75 |
| 1 to 2 | 48.80 |
| 2 to 4 | 97.75 |
| More than 4 | 195.50 |

5.1.3 Knowing the length of the equivalent cantilever the pile head deflection (Y) shall be computed using the following equations:

$$Y = \frac{Q(L_1 + L_F)^3}{3 EI} \quad \text{for free head pile} \quad = \quad \frac{Q(L_1 + L_F)^3}{12 EI} \quad \text{for fixed head pile}$$

where Q is the lateral load

5.2 Admissible Deflection to Decide the Safe Lateral Load as per BIS : The BIS Code for lateral load testing on piles specifies that safe lateral load on the pile shall be taken as the least of the followings displacements to be considered at the cut-off level of the pile :

- Fifty percent of the final load at which the total displacement increases to 12 mm
- Final load at which the total displacement corresponds to 5 mm and
- Load corresponding to any other specified displacement as per performance criteria.

It will thus be seen that the stipulations of the code based on empirical method specifies that the safe lateral load capacity of a pile foundation should determine on the basis of a deflection of 5 mm at the cut off level of the pile for an individual pile.

5.3 The Safe Lateral Capacity Determination : The authors, as such based on the soil bore data and classification as well as the physical properties of the pile has worked out values of L_f and $K1/K2$ as per para 5.1.2 above. The effects of layered soil have been considered by repeated trial i.e. at the first instance only the value of $K1/K2$ for the top soil has been taken and when L_f exceeds the depth of the top layer weighted average of $K1/K2$ has been taken based on the depth of the layers between L_f . After a few trials the L_f considering the weighted average of value of $K1$ or $K2$ equals the calculated value. Once the L_1 and L_f are known the safe lateral load for individual pile has been determined as equal to Q which produces a deflection (Y) of 5 mm at the pile head level.



Effect of group action has not been considered due to the complexities involved but the spacings of the piles have been kept at least 3 times the diameter of the pile.

5.4 Analysis of Load Test Results : The lateral load capacity of individual piles have been calculated by the authors using the above method for some of the projects. Subsequently the pile have been load tested for lateral load after their installations. The sites constituted mainly of non-cohesive soil though top layer has been silty sand or silty clay, with predomination of silt.

It has been observed that the load deflection curve changes its slope drastically near or just beyond the theoretical safe lateral load as calculated above. Lateral deflection observed at the top of the pile at this load hardly reaches 1 mm but after crossing this load the rates of deflection per unit lateral load increases substantially. These results often indicated that a very conservative value of safe lateral load is being considered for the design. But considering the various factors that effects the lateral load capacity in the long term due to repeated loading, group effect, creep of soil etc. the method adopted in deciding the lateral load capacity of the piles for the design appears rational.

6.0 CONCLUSIONS

From the above, it can be concluded that determination of lateral load capacity of pile foundation system is reasonably complex and simplified approach adopting empirical values of soil properties and empirical methods needs to be considered.

It will however, be desirable to decide the vertical design capacity of pile judiciously, even for the layered soil considering the codal provisions of the country.

It is very difficult to make an elastic analysis of pile group subject to lateral load when these also subjected to vertical load. Load testing of piles concurrently with vertical and lateral load is not possible although in actual, the soil surrounding the piles is subjected to both lateral and vertical strains/stresses be it in elastic conditions or plastic condition. As such a little conservative approach in the safe design for lateral capacity of piles is worth.

It is also suggested that the pile test shall be conducted adjacent to the boring area in order to study the test data in conjunction with boring data. The use of pile foundation for bridges with deep scours and without any possibility of socketing at the bottom needs serious examination and perhaps more research before adopting.

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