Lateral Bearing Capacity of Piles in Cohesive Soils Based on Mohr-Coulomb Yield Criterion

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Abstract
This paper presents the results of a series of numerical analysis which carried out on piles in cohesive soils. In this study a finite element program which was developed at International University of Imam Khomeini, Qazvin, Iran, is used. This 3D finite element program (3DFEM 4.1) uses Mohr-Coulomb yield criterion as failure mechanism. The objective of this study is to suggest a series of graphs to simplify the procedure of pile design in cohesive soils under lateral loading. Broms proposed graphs to obtain ultimate lateral bearing capacity of such piles. However, the graphs do not cover all piles with different lengths. Therefore, it seems that the design graphs which he proposed should be modified
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Keywords: Lateral Bearing Capacity, Mohr-Coulomb, Pile, Cohesive Soil, Numerical analysis.

1. INTRODUCTION

Lateral loads and moments may act on piles in addition to the axial loads. Axial downward loads are due to gravity effects. Upward loads, lateral loads, and moments are generally due to forces such as wind, waves and earthquake. The basic elements of geotechnical engineering are described in a number of standard geotechnical engineering textbooks (Holtz and Kovacs, 1981; Terzaghi et al., 1996; Coduto, 1999; Das, 2002). The allowable lateral loads on piles are determined from the following two criteria:

1- Allowable lateral load is obtained by dividing the ultimate (failure) load by an adequate factor of safety.
2- Allowable lateral load is corresponding to an acceptable lateral deflection.

The smaller of the two above values is the one actually adopted as the design lateral load. For profiles having a gradual increase of stiffness with depth, foundation stiffness can often be reasonably estimated using half space formulations (Stewart et al., 2003). Methods of calculating lateral resistance of vertical piles can be broadly divided into two categories:

1- Methods of calculating ultimate lateral resistance.
2- Methods of calculating acceptable deflection at working lateral load.

2. METHODS OF CALCULATING LATERAL RESISTANCE OF VERTICAL PILES:

Brinch Hansen's Method (Brinch Hansen, 1961): This method is based on earth pressure theory and has the advantage that it is:

1- Applicable for c-□ soils.
2- Applicable for layered system.

However, this method suffers from disadvantages that it is:

3- Applicable only for short piles.
4- Requires trial and error solution to locate point of rotation.

Broms' Method (Broms, 1964): This also is based on earth pressure theory, but simplifying assumptions are made for distribution of ultimate soil resistance along the pile length. This method has the advantage that it is:

1- Applicable for short and long piles.
2- Considers both purely cohesive and cohesionless soils.

3- Considers both free-head and fixed-head piles that can be analyzed separately.

However, this method suffers from disadvantages that:

1- It is not applicable to layered system.
2- It does not consider c-□ soils.

There are some more problems in this method, which we will discuss later.

The ultimate bearing capacity is often difficult to assess even by means of a static loading test. The oldest approach is simply to state that the ultimate load in a test is equal to the applied load when the movement of the pile head is 10 percent of the pile toe diameter. Vesic (1977) listed this definition and some others based on movement of the pile head. Fellenius (1975, 1980) presented a comparison of nine methods based on the shape of the load-movement curve.

3. METHODS OF CALCULATING ACCEPTABLE DEFLECTION AT WORKING LOAD MODULUS OF SUB GRADE REACTION APPROACH

In this method it is assumed that soil acts as a series of independent linearly elastic springs (Matlock, 1962). This method has the advantage that:

1. It is relatively simple.
2. It can incorporate factors such as nonlinearity, variation of sub grade reaction with depth, and layered systems.
3. It has been used in the practice for a long time.

Therefore, a considerable amount of experience has been gained in applying the theory to practical problems. However, this method suffers from disadvantages that:

1. It ignores continuity of the soil.
2. Modulus of subgrade reaction is not a unique soil property but depends on the foundation size and deflections.

Elastic Approach: In this method, the soil is assumed as an ideal elastic continuum (Poulos, 1971). The method has the advantage that:

1. It is based on a theoretically more realistic approach.
2. It can give solutions for varying modulus with depth and layered system.

However, this method suffers from disadvantages that:

1. It is difficult to determine appropriate strains in a field problem and the corresponding soil modules.
2. It needs more field verification by applying theory to practical problems.

Verification studies by Kim and Stewart (2003) showed that these procedures are generally not suitable for deep piles. The structural design of deep foundation elements generally requires direct structural modeling of pile response to head loads. These models generally model the pile as a beam-column element and the soil with distributed reaction springs (Nikolaou et al., 2001; Mylonakis, 2001).

The objective of this study is to suggest a series of graphs to simplify the procedure of pile design in cohesive soils. The investigations were carried out by varying the length of piles. Also different combinations of lateral force and moment are used. We also use different diameter of piles to investigate its effect. All of these analyses were carried on six different kinds of clays (Cu=10, 20, 30, 40, 50, 60 kN/m2). One of Broms' solutions is that he does not consider effect of vertical loading on lateral bearing capacity of piles. In this study we consider this effect, and present design graphs to simplify design procedures.

3. ANALYSIS CONSIDERATIONS

The geometry of a typical finite element model adopted for the analysis is shown in Fig1. Finite element analyses were carried out by applying horizontal loads on top of pile. To simulate applied moment just as Broms did, we use an extra length on top of pile. Lateral soil-pile interaction model is elastic-perfectly plastic, and pile is flexible. To obtain the ultimate load, we start from a small lateral load, and then increase it to reach the failure.

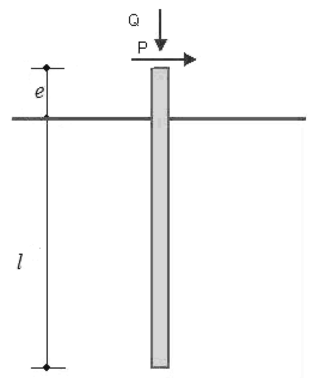

Fig 1. Geometry of model

In the field, development and measurement of large-strain soil behavior is more difficult and few proven techniques are available. An in situ borehole torsional test (Henke and Henke, 1991) advances two thin concentric tubes into the soil below the bottom of a boring. Torque is applied to the inner tube and used, along with its measured rotation, to evaluate the stress–strain behavior of the soil. Riemer et al. (2001) have developed a similar device for measuring dynamic properties of cohesive soil deposits.

Material properties which are used are based on software recommendations which are in agreement with experimental evidence. Also three different diameters (0.5, 0.8 and 1.0 m) are used to investigate its influence.

3. RESULTS OF FINITE ELEMENT ANALYSIS

3.1 EFFECT OF SOIL TYPE

At first a series of analyses have done on different fully saturated clays with different e/B (e is free distance over the soil surface and B is pile diameter) and varying l/B (l is the length of pile), and the results compared to Broms' graphs. In order to consider a range of different combinations of loads and moments we consider four ratios, which are e/B=0, 1, 2, 4. In this stage we found that his assumption on ultimate resistance is not true. He has assumed that the ultimate resistance of clays is 9BCu, but the results show that soil will collapse much sooner, see Figs. 2-5.

Broms divided piles into two groups. First group is short piles and second group is long piles. He used two different graphs to present the results. In this study cleared that although the behavior of short piles and long piles differ, but the places which maximum resistance occur dose not change much. So we put them in one graph. In order to cover a range of usual pile lengths we consider different ratios, which are l/B=4, 6, 8, …, 20. Therefore, in this approach, piles which are not in Broms' category (piles between short and long piles) can now be considered.

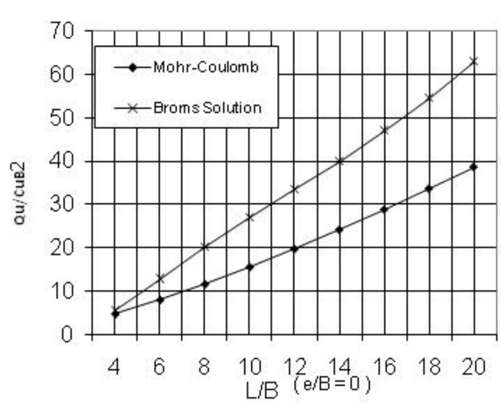

Fig 2. Mohr-Coulomb yield criterion in comparison to Broms' method (e/B=0)

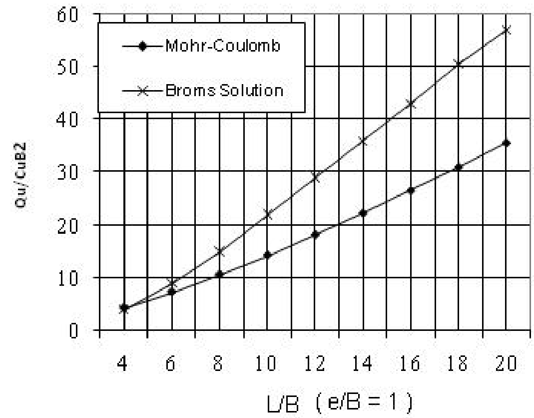

Fig 3. Mohr-Coulomb yield criterion in comparison to Broms' method (e/B=1)

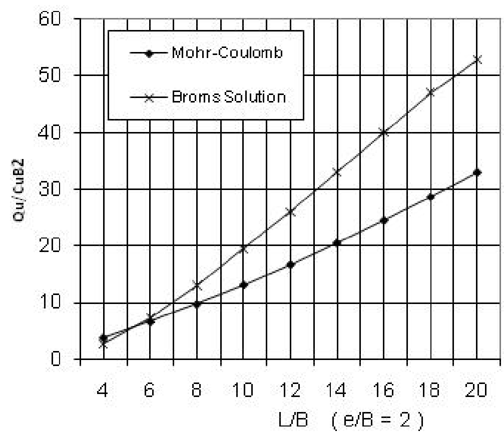

Fig 4. Mohr-Coulomb yield criterion in comparison to Broms' method (e/B=2)

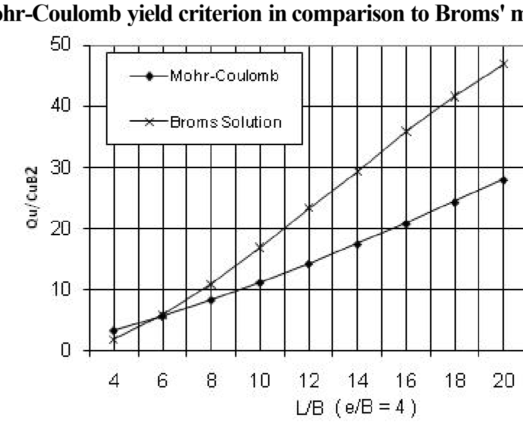

Fig 5. Mohr-Coulomb yield criterion in comparison to Broms' method (e/B=4)

3.2 EFFECT OF DIAMETER:

In order to present more general design graphs, in next step we repeated our analyses with different diameters to investigate its influence, see Fig. 6. As it is shown diameter does not change the normalized ultimate lateral bearing capacity.

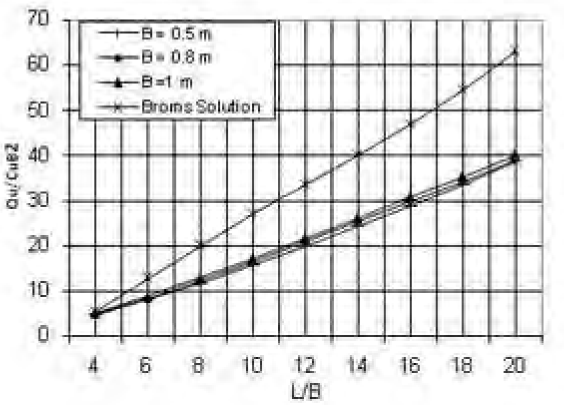

Fig 6. Effect of diameter on cohesive soils

The results show that Mohr-Coulomb yield criterion could estimate soil behavior very well. After performing more than 648 analyses, following formulas were approximated:

$$Q_u = 0.74\left(\frac{l}{B}\right)^{1.32} \exp\left(-0.08\frac{\mathrm{e}}{B}\right) C_u B^2 \tag{1}$$

Where Qu is ultimate lateral bearing capacity of a pile.

3.3 EFFECT OF VERTICAL LOADING

In previous analyses just as Broms' assumptions, the vertical load did not considered. But again to make our graphs more general, and also to investigate the influence of vertical load on ultimate lateral bearing capacity, we consider it. Based on the model, axial load reduces moment capacity of the pile. In this stage, in every analysis, first we found the ultimate vertical bearing capacity. To do this we start from a small axial load and then increase it to reach the failure, then by use of a factor of safety of 3 the allowable vertical load is applied, and finally the ultimate lateral bearing capacity of pile is determined. The obtained results of these processes are presented in Fig. 7. The results show that the ultimate lateral load will not change greatly due to vertical load.

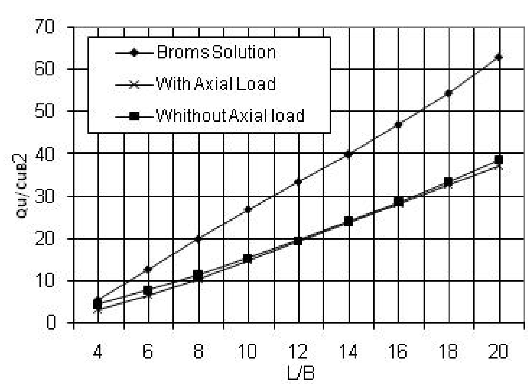

Fig7. Effect of vertical load on cohesive soils (e/B=0)

4. CONCLUSIONS

Conclusions: A series of numerical analysis has been carried out to evaluate the ultimate lateral bearing capacity of a pile in cohesive soils. The study primarily aimed at presenting design graphs which they can cover all piles with different lengths, and also checked the failure criteria which Broms has proposed. In this study all of the analyses have done on different types of cohesive soils and the following results are obtained:

1. We found that Broms assumption is overestimated.
2. For more practical reasons we applied vertical allowable load. It was shown that vertical allowable load would not greatly change ultimate lateral bearing capacity of a pile.
3. In this study by considering different effects, more general graphs were presented.
4. The effect of pile diameter was studied, and it was concluded that diameter would not affect the normalized ultimate bearing capacity.
5. Different soil types were analyzed and a formula suggested calculating lateral bearing capacity of piles.

5. REFERENCES

1. Brinch Hansen, J. (1961), "The Ultimate Resistance of Rigid Piles Against Transversal Forces", Danish Geotechnical Institute (Geoteknisk Institut) Bull. No. 12, Copenhagen, p.5-9.
2. Broms, B. (1964), "The Lateral Resistance of Piles in Cohesive Soils", J. Soil Mech. Found. Div., ASCE, Vol. 90, No. SM2, March 1964, pp.27-63.
3. Coduto, D.P. (1999), Geotechnical Engineering: Principles and Practices, 5th ed., Prentice Hall, Upper Saddle River, NJ, 759 pp.
4. Das, B.M. (2002), Principles of Geotechnical Engineering, Brooks/Cole, Pacific Grove, CA, 589 pp.
5. Fellenius, B.H. (1975), "Test loading of piles. Methods, interpretation and new proof testing procedure", Journal of Geotechnical Engineering, ASCE, 101, No. GT-9, pp. 855-869.
6. Fellenius, B.H. (1980), "The analysis of results from routine pile loading tests", Ground Engineering, London, 13, No. 6, pp. 19-31.
7. Henke, W. and Henke, R. (1991), "In situ torsional cylindrical shear test — laboratory results", Proceedings, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, 1, 131–136.
8. Holtz, R.D. and Kovacs, W.D. (1981), An Introduction to Geotechnical Engineering, Prentice-Hall, Englewood Cliffs, NJ, 733 pp.
9. Kim, S. and Stewart, J.P. (2003), "Kinematic soil-structure interaction from strong motion recordings", J. Geotech. Geoenviron. Eng., ASCE, 129, 323–335.
10. Matlock, H. and Reese, L. C. (1962), "Generalized Solutions for Laterally Loaded Piles", Transactions of the American Society of Civil Engineers, Vol. 127, part 1, pp.1220-1247.
11. Mylonakis, G. (2001), "Simplified model for seismic pile bending at soil layer interfaces", Soils and Foundations, 41 (4), 47–58.
12. Nicolaou, S., Mylonakis, G., Gazetas, G. and Tazoh, T. (2001), "Kinematic pile bending during earthquakes: Analysis and field measurements", Geotechnique, 51 (5), 425–440.
13. Poulos, H.G. (1971), "Behavior of Laterally Loaded Piles: I-Single Piles", J. Soil Mech. Found. Div. ASCE, Vol. 97, No. SM 5 , pp. 711-731.
14. Riemer, M. F., Grizzle, C., and Safaqah, O. (2001), "Measurement of dynamic properties of clay using the downhole freestanding shear device", Proc. Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri-Rolla, Rolla, Missouri, 6 pp., Paper No. 1.38.
15. Stewart, J.P., Kim, S., Bielak, J., Dobry, R., and Power, M. (2003), "Revisions to soil structure interaction procedures in NEHRP design provisions", Earthquake Spectra. 19, 677–696.
16. Terzaghi, K., Peck, R.B., and Mesri, G. (1996), Soil Mechanics in Engineering Practice, Wiley Interscience, New York, 592 pp.

17. Vesic, A.S. (1977), "Design of Pile Foundations", National Cooperative Highway Research Program, Transportation Research Board, National Research Council, National Academy of Sciences, Washington, Synthesis of Highway Practice No. 42.

18. Areias, P. M. A. and Belytschko, T. (2005), "Analysis of Three-Dimensional Crack Initiation and Propagation Using the Extended Finite Element Method," International Journal for Numerical Methods in Engineering, **63** (55), pp. 760–788.

19. Atluri, S. N. and Shen, S. (2002), "*The Meshless Local Petrov–Galerkin (MLPG) Method",* Tech Science Press, USA.

20. Udwadia, F. E. and Trifunac, M. D. (1973), "Ambient Vibration Test of Full Scale Structures," Proc. of the 5th World Conf. On Earthquake Engineering, Rome, pp. 135-142.

21. Aghayani-pour, K. and Hakemifar, J. (2003), "Theoretical and Experimental Study of the Strength of Piezoelectric Structures Under Pressure Forces," Proc. of the 1st Conference on Dynamics of Advanced Structures, Mechanics Research Center, Isfahan, pp. 23-25, (in Persian).

22. Trifunac, M. D. (1970), "*Wind and Microtremor Induced Vibration of a 22 Story Steel Frame Building,"* Earthquake Engineering Research Lab., Report EERL 70-01, California Institute of Technology, Pasadena California.

23. Sethian, J. A. (2006), "*Moving interfaces and boundaries: level set methods and fast marching methods,"* http://math.berkeley.edu/~sethian/Explanations/level_set_explain.html.