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Development of Bearing Capacity Factor in Clay Soil with Normalized Undrained Shear Strength Behavior using The Finite Element Method

Aswin Lim

Faculty of Engineering, Civil Engineering Department, Parahyangan Catholic University
Jl. Ciumbuleuit No. 94 Bandung 40141, email: aswinlim@home.unpar.ac.id

Abstract

This paper presents a development of bearing capacity factor chart for strip footing laying on clay soil with normalized undrained shear strength using finite element method. Since stress history and normalized soil engineering properties concept were introduced in 1974 by Ladd and Foot, the new approach of design for clays has evolved. In order to accommodate this new approach, a study is conducted to see the effect of the normalized soil properties on bearing capacity factor, especially footings on clays. The results show that the effect of normalized undrained shear strength is more sensitive for soft clays rather than stiff clays.

Keywords: *Bearing capacity factor, normalized undrained shear strength.*

Abstrak

Makalah ini menyajikan pengembangan grafik faktor daya dukung untuk pondasi lajur pada tanah lempung dengan normalisasi kuat geser tak terdrainase tanah menggunakan metode elemen hingga. Sejak konsep historik tegangan dan normalisasi properti teknik tanah yang diperkenalkan pada tahun 1974 oleh Ladd dan Foot, pendekatan baru untuk perencanaan untuk tanah lempung telah berevolusi. Untuk mengakomodasi pendekatan baru ini, sebuah studi dilakukan untuk mempelajari efek dari normalisasi properti tanah pada faktor daya dukung, khususnya pondasi pada tanah lempung. Hasil studi menunjukkan bahwa efek normalisasi kuat geser tak terdrainase lebih sensitif terhadap lempung lunak dibandingkan lempung teguh.

Kata-kata Kunci: *Faktor daya dukung, normalisasi kuat geser tak terdrainase.*

1. Introduction

Bearing capacity of strip footing has received much attention in literature. Terzaghi (1943) was the first to present a comprehensive theory for the evaluation of the ultimate bearing capacity of rough shallow foundations. In 1963, Meyerhof suggested modification of Terzaghi's bearing capacity formulation by adding several factors such as shape factors, depth factors, and load inclination factors. The main modification from Meyerhof was the consideration of the shearing resistance along the failure surface in soil above the bottom of the foundation. However, from the laboratory and field studies of bearing capacity, the failure surface in soil suggested by Meyerhof is more similar compared to Terzaghi ones. If this change is accepted, the value of bearing capacity factor (Nc) is 5.14 rather than 5.7 in clay soil (ϕ=0) condition. All of the theories proposed by Terzaghi and Meyerhof were based on the limit equilibrium method.

In addition to the limit equilibrium method, there are several methods such as the limit analysis approach, semi empirical approach and finite element method. Valverd, et al., (2010) conducted the study of prediction of bearing capacity factor of shallow foundation by three dimension finite element method. The results of their study showed a good agreement between finite element method and the limit equilibrium method. Zhu (2004) also conducted a study of bearing capacity factor of shallow foundation on two layers clays using finite element method. The result of his study also showed a good agreement with the limit analysis solution.

An application of the finite element method of shallow foundation is presented in this paper. From limit equilibrium solution, the clay soil is always assumed as a homogeneous layer with the constant undrained shear strength value. However, Ladd and Foot (1974) has introduced Stress History and Normalized Soil Engineering Properties (abbreviated as SHANSHEP) concept as a new method of design. The most frequently used normalized soil properties is S_u/σ'_v ;

in which σ'_v is in-situ soil vertical effective stress. This paper focuses on developing bearing capacity factor in clays, at which the soil undrained shear strength increasing with depth, which is based on SHANSHEP concept.

2. Numerical Modeling of Shallow Foundation

PLAXIS V.8.2 software is assigned as a tool for the numerical simulation. In simulation, the triangle element with 15 nodes is selected which could produce high quality stress results. A schematic plane strain diagram for the simulation of the strip footing laying on clay soil is shown in **Figure 1**. The input of normalized undrained shear strength parameter is utilizing $c_{increment}$ feature in PLAXIS which is the soil undrained shear strength increasing with depth. The normalized undrained shear strength is affecting all soil elements since the soil is assumed homogenous. The width of foundation (B) is assumed 2 meters and the foundation is assumed rigid and rough. In the finite element model, due to symmetry, only half of the foundation width (0.5B) is modeled as illustrated in **Figure 2**. The length and height of the finite element model are 7.5B and 5B, respectively. This size of finite element model is large enough to keep the boundary conditions effects due to footing loads. The boundary condition is fixed at bottom part and roll at the both sides. A node named A is selected right below the foundation in order to check the load-displacement curve which is shown in **Figure 2**

The elastic-perfectly plastic Mohr-Coulomb (ϕ=0) model is used as the soil model in this study. The initial undrained shear strength of clay soil is equal to several values based on the soil consistency that proposed by Terzaghi and Peck (1967) as shown in **Table 1**. For developing the bearing capacity factor chart, four values of initial undrained shear strength (i.e. 12 kPa, 25 kPa, 50 kPa, and 100 kPa) are used as input values. Those four values reflect the consistency of clay soil. Then, twenty variations of S_u/σ'_v (i.e. 0, 0.1, 0.15, …,1.0) are used as input values as well for each initial undrained shear strength. Thus, eighty simulations are performed in order to develop the bearing capacity factor chart. All of the simulation are performed with over consolidation ratio (OCR) is equal to unity in order to generalized the problem. The elastic properties of clay soil are assumed as E_u/S_u equals 500 (the undrained Young's modulus depends on the undrained shear strength) and the υ_u (undrained poisson's ratio) is equal to 0.495. Since the undrained shear strength follows the SHANSHEP concept, neither does the undrained Young's modulus.

Table 1. The relationship between consistency of cohesive soils and undrained shear strength (Terzaghi and Peck, 1967)

No	Consistency	Su (kPa)
1	Very soft	< 12
2	Soft	12-25
3	Medium	25 -50
4	Stiff	50 - 100
5	Very stiff	100 - 200
6	Hard	> 200

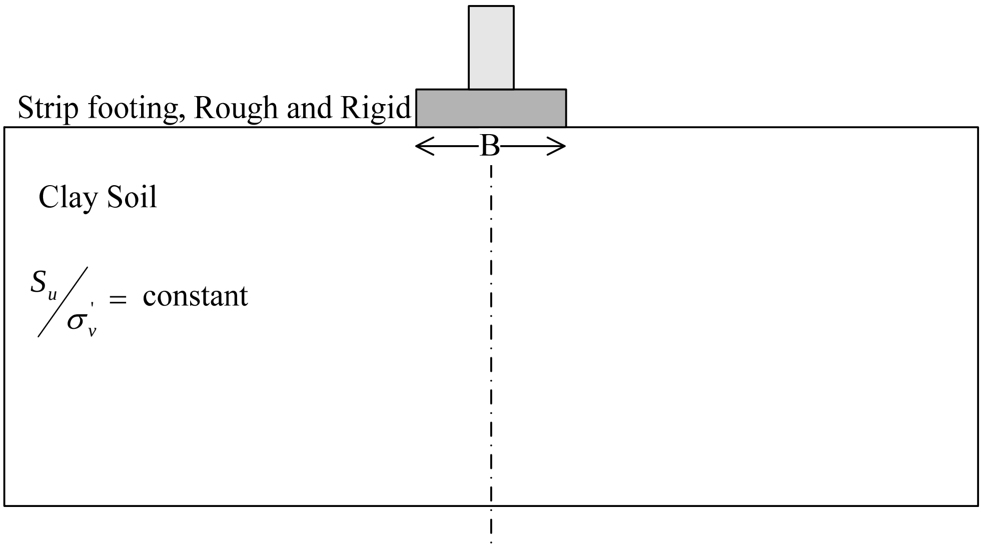

Figure 1. A schematic plane strain diagram to simulate the strip footing laying on clay soil

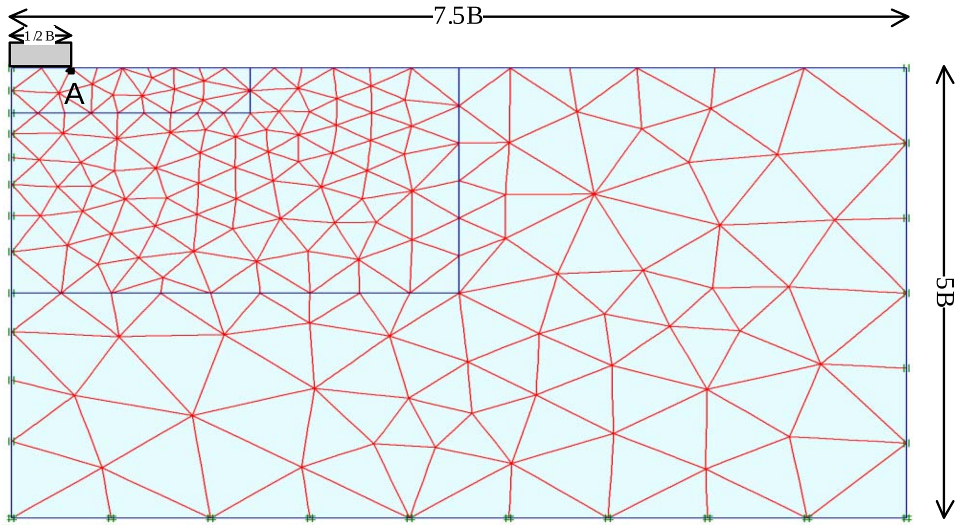

Figure 2. Finite element mesh to simulate the strip footing laying on clay soil

The analysis was performed under a load increment control. For each simulation, the uniformly distributed load is applied on the soil with a constant width 0.5B until the soil failure. Then a node is selected right below the foundation in order to check the load-displacement curve. From the load displacement curve which is shown in **Figure 3**, the load correspondent to the clear plateau is the ultimate bearing capacity (q_u) of the footing. The load displacement curve which reaches clear plateau also indicates that the soil has reached failure. The bearing capacity factor (N_c) can be calculated by **Equation (1)**.

$$N_c = \frac{q_u}{S_u} \quad (1)$$

3. Results and Discussion

From eighty simulations performed with variation of initial undrained shear strength and S_u/σ'_v, bearing capacity factor chart is developed as shown in **Figure 4**. For each simulation, the bearing capacity factor is plotted together with the normalized undrained shear strength. The data for each initial undrained shear strength simulation tends to form a straight line. Using the regression method, the straight line is drawn. Classification of the cohesive soil consistency area of the chart is shown in **Figure 5**. The classification area of clay soil consistency is based on **Table 1** which is proposed by Terzaghi and Peck (1967). From **Figure 5**, it is shown that when the normalized undrained shear strength is equal to zero, meaning that the undrained shear strength is constant from top to bottom of a layer of soil, for all soil consistency, the bearing capacity factor is equal to 5.16. This value shows a good agreement with the limit equilibrium method proposed by Meyerhof (1963) which yielded 5.14 for ϕ=0. While the normalized shear strength increases, the bearing capacity factor also yields in the same tendency. The amount of increment of bearing capacity factor depends on consistency of the soil. The softer soil yields greater increment of bearing capacity factor and vice versa. In other words, the effect of normalized undrained shear strength is more sensitive for soft clay than stiff clay.

Another effect of normalized undrained shear strength could be seen from the amount of soil displacement. As shown in **Figure 6**, the plastic zone for clay soil with normalized undrained shear strength is smaller than clay soil without normalized shear strength. The plastic zone for clay soil with normalized undrained shear strength shaped like bulb with 1.4B in height and around B in width, while for clay soil without normalized undrained shear strength, the height is 2.25B and the width is 1.75B with bulb shape also. The area of plastic zone can reflect the amount of displacement occurred. The larger the plastic zone, of course, yields larger soil displacement.

4. Parametric Study

A parametric study was conducted to study the effect of undrained Young's modulus to the bearing capacity factor. Forty four simulations were performed with various initial undrained shear strength such as 12 KPa, 25 kPa, 50 KPa, and 100 KPa. The normalized undrained Young's modulus, E_u/S_u equals 300 which is different from previous ones. The result is shown in **Table 2**. As shown in **Table 2**, there is no significant difference of bearing capacity factor value when E_u/S_u = 500 and E_u/S_u = 300. The reason is the ultimate bearing capacity controlled by undrained shear strength, not the undrained Young's modulus. In other words, the undrained shear strength is the main factor controlling the soil ultimate bearing capacity, since the failure of soil body depends on the undrained shear strength based to the Mohr-Coulomb failure criterion. In addition, the undrained Young's modulus is controlling the elastic condition of soil body which is not in failure or plastic condition.

5. Conclusion

Five conclusions is drawn from this study, such as :

1. Bearing capacity factor chart for normalized undrained shear strength behavior of clay soil has been developed in this paper.
2. Two assumptions made in developing the chart: (1) the E_u/S_u is equal to 500 for all type of soil consistency and (2) the Over Consolidation Ratio (OCR) equals unity (normally consolidated clay).
3. Since the soil bearing capacity only depends on the undrained shear strength, thus the undrained Young's modulus parameter (E_u) is not significant in affecting bearing capacity factor.
4. The effect of normalized undrained shear strength is more sensitive to soft clay than stiff clay.
5. The amount of soil displacement is greater for soils without using normalized undrained shear strength compare to soils that using normalized undrained shear strength.

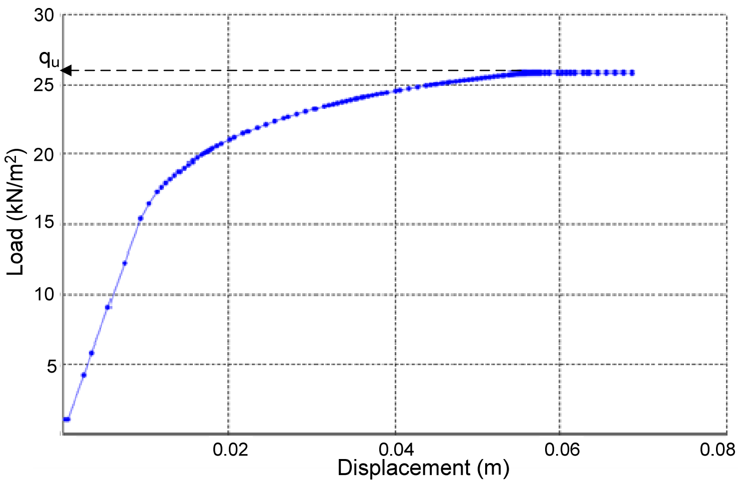

Figure 3. Typical load displacement curve of strip footing

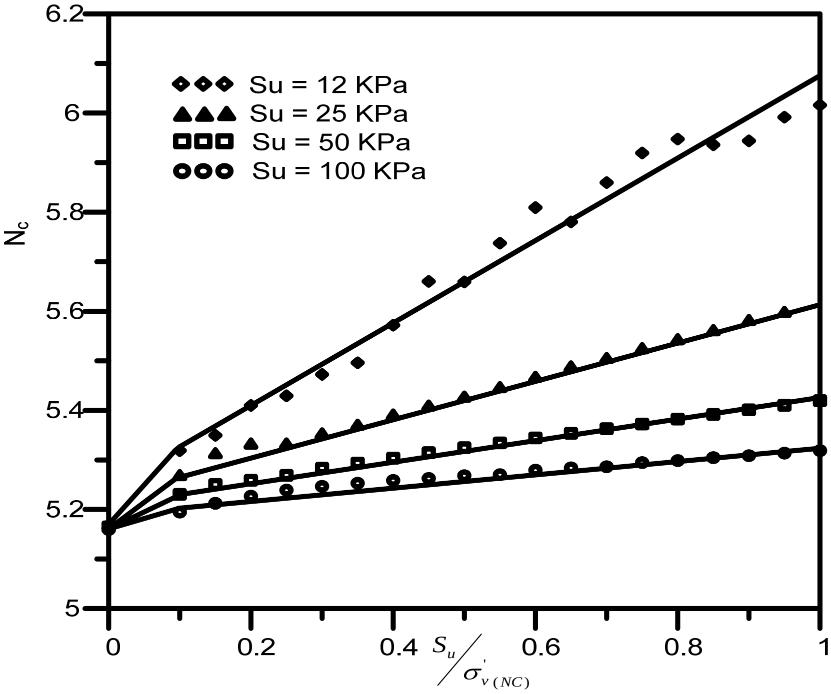

Figure 4. Raw bearing capacity factor chart

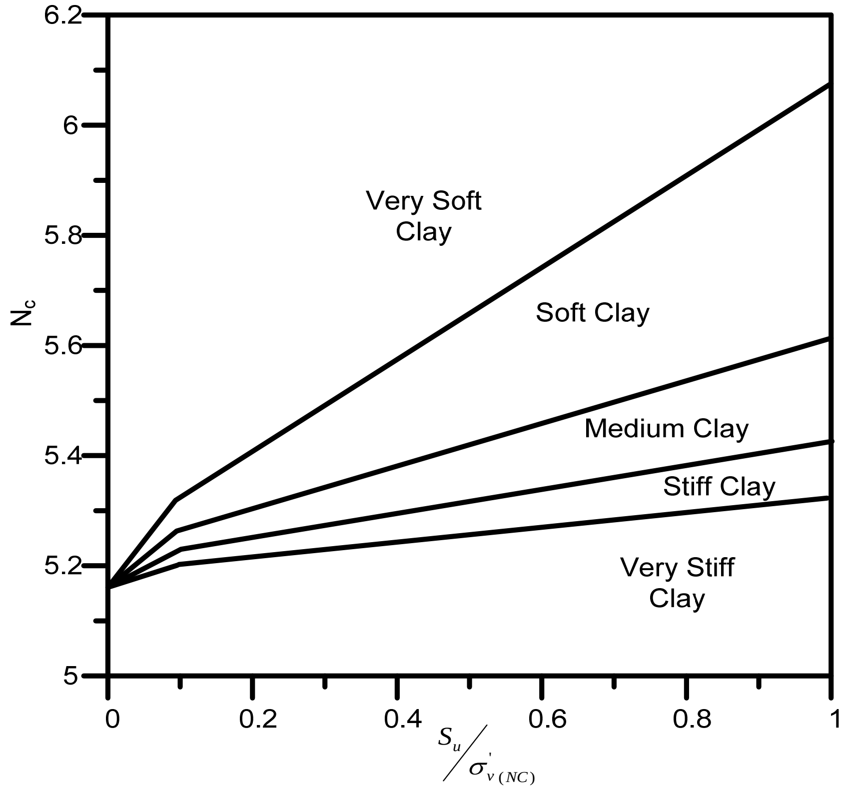

Figure 5. Bearing capacity factor chart for clay soil with normalized undrained shear strength parameter

Table 2. The bearing capacity factor comparison between E_u/S_u = 300 and E_u/S_u = 500

S_u/σ_v'	Nc Su = 12 KPa		Nc Su = 25 KPa		Nc Su = 50 KPa		Nc Su = 100 KPa	
	E_u/S_u = 500	E_u/S_u = 300	E_u/S_u = 500	E_u/S_u = 300	E_u/S_u = 500	E_u/S_u = 300	E_u/S_u = 500	E_u/S_u = 300
0	5.168	5.168	5.17	5.17	5.165	5.165	5.159	5.161
0.1	5.318	5.318	5.27	5.27	5.23	5.23	5.195	5.194
0.2	5.41	5.388	5.33	5.308	5.259	5.259	5.226	5.226
0.3	5.472	5.472	5.35	5.35	5.283	5.283	5.246	5.246
0.4	5.571	5.569	5.39	5.39	5.303	5.303	5.258	5.258
0.5	5.659	5.659	5.425	5.425	5.324	5.324	5.268	5.268
0.6	5.809	5.809	5.465	5.465	5.344	5.344	5.279	5.279
0.7	5.859	5.859	5.5	5.5	5.363	5.362	5.286	5.286
0.8	5.947	5.947	5.54	5.54	5.382	5.382	5.298	5.298
0.9	5.943	5.943	5.58	5.58	5.4	5.401	5.308	5.308
1	6.016	6.016	5.505	5.505	5.419	5.419	5.318	5.318

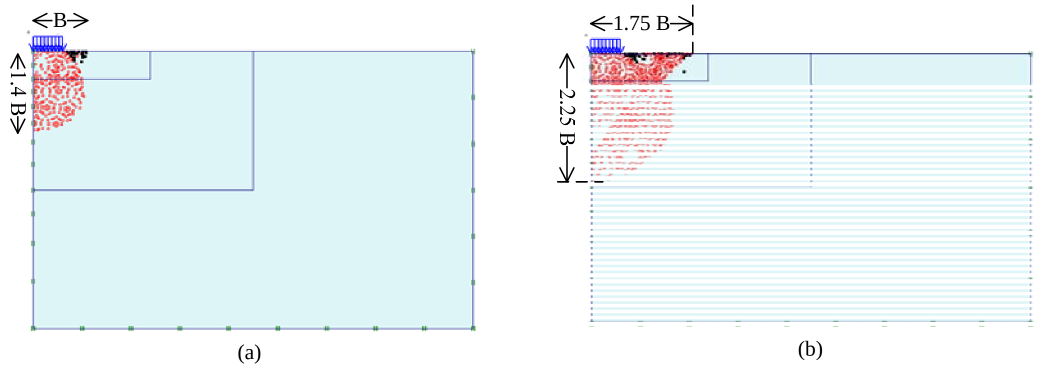

Figure 6. Typical plastic zone for (a) soil with normalized undrained shear strength and (b) soil without normalized undrained shear strength

References

Ladd, C.C., and Foot, R., 1974, New Design Procedure for Stability of Soft Clays, *Journal of Geotechnical Engineering Division*, ASCE, Vol. 100, pp. 763-786.

Ladd, C.C., Foot, R., Ishihara, K., Schlosser, F., and Poulos, H.G., 1977, *Stress Deformation and Strength Characteristics*, State of The Art Report, Proc. 9th ICSMFE, Tokyo, pp. 421-494.

Meyerhof, G.G. 1963, Some Recent Research on the Bearing Capacity of Foundations, *Canadian Geotechnical Journal*, Vol. 1, pp. 16-26.

Terzaghi, K., 1943, *Theoretical Soil Mechanics*, New York: Wiley.

Terzaghi, K., and Peck, R.B., 1967, *Soil Mechanics in Engineering Practice*, 2nd edition, New York: John Wiley.

Valverd, N.N., Nogueira, C.L., and Romanel, C., 2010, FE Prediction of Bearing Capacity Factor of Shallow Foundation Under Three-Dimensional Strain Condition, *Mechanics Computational*, Vol. XXIX, Buenos Aires, pp. 4541-4554.

Zhu, M., 2004, *Bearing Capacity of Strips Fottings on Two-layer Clay Soil by Finite Element Method*, ABAQUS User's Conference, pp. 777-787

Appendix

An application example of the bearing capacity factor chart for clay soil with normalized undrained shear strength parameter is shown here. A strip footing with the width equals 1.5 m is constructed on clays with initial undrained shear strength equals 20 kPa and the soil unit weight equals 18 kN/m^3. The normalized undrained shear strength is equal to 0.25 and from consolidation test, the over consolidation ratio equals to 1.5. The problem illustration is shown in **Figure A-1**.

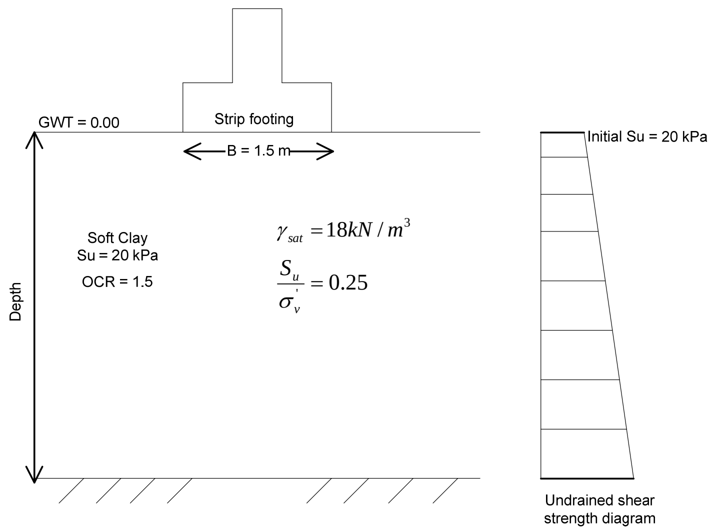

Figure A-1. Problem illustration

Since, the soil is overly consolidated, then the normalized undrained shear strength value should be converted to normally consolidated condition by **Equation (A-1)** which is proposed by Ladd et al., (1977).

$$\frac{\left(S_u/\sigma_v'\right)(OC)}{\left(S_u/\sigma_v'\right)(NC)} = OCR^m \qquad \text{(A-1)}$$

Where m = 0.8 (empirical)

After converted to the normalized undrained shear strength in normally consolidated condition which is equal to 0.18 by **Equation (A-1)**, then the bearing capacity factor chart is ready to be used. With the initial undrained shear strength equals 20 kPa, the soil is classified as soft clay. From **Figure A-2**, the bearing capacity factor (Nc) is equal to 5.34. By using **Equation 1**, the soil bearing capacity (q_u) is multiplication of initial undrained shear strength by bearing capacity factor. Thus, the soil bearing capacity is equal

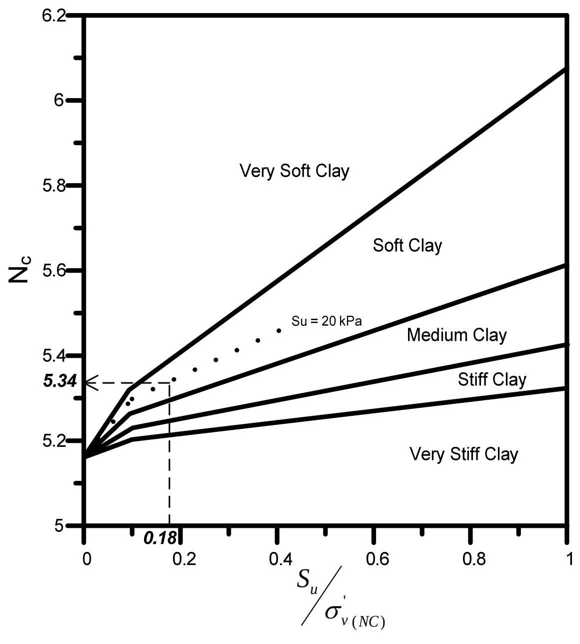

Figure A-2. Example of chart plotting for typical normalized undrained shear strength