

# Prediction of Drained Settlement and Ultimate Bearing Capacity for Stone Columns Supported Foundation

Kok Shien Ng<sup>(✉)</sup>

Faculty of Civil Engineering, Universiti Teknologi MARA,  
Pulau Pinang Branch, 13500 Permatang Pauh, Penang, Malaysia  
ngkokshien@ppinang.uitm.edu.my

**Abstract.** This paper presents a validation of simplified design approach against a field study and a laboratory test. The design approach has been developed to predict drained settlement and the ultimate bearing capacity of stone columns supported foundation adopting a hyperbolic relationship to simulate the strain hardening behavior. The result of a plain footing load test is required to give two curve fitting parameters and then adapted them by introducing a reduction factor which take into account the length ratio and the area replacement ratio to predict the stress-strain characteristic of a stone column supported foundation. Good agreements are found when the predictions using the simplified approach are compared with the laboratory testing and field case study.

## 1 Introduction

Stone columns has been used intensively all around the world to improve the subsoil for supporting many civil infrastructure including road and railway embankment, building, factory, large storage tank, etc. that can tolerate some settlements. Design of stone columns supported foundation is often carried out in two steps. First, it has to be checked for the ultimate bearing capacity. Second, serviceability check is performed particularly on the long term drained settlement which is usually more critical.

Stone columns are used in groups and can be installed either as end bearing or floating type. Most of the stone column design is catered for end bearing columns (Balaam and Booker 1981; Priebe 1995; Han and Ye 2001; Castro and Sagasetta 2009) and very little for floating columns (Rao and Ranjan 1985; Lawton et al. 1994; Shahu and Reddy 2014; Ng and Tan 2014; Bouassida and Carter 2014). Many model tests (either laboratory or numerical) and field tests have been performed to study different aspects of stone column behavior such as settlement, consolidation rate, ultimate bearing capacity, failure modes, load sharing, group performance, etc. (Babu et al. 2013; Najjar 2013; Bouassida and Hazzar 2015). Based on limit analysis, Bouassida et al. (2009) proposed an analytical solution to predict the bearing capacity of a rigid foundation on a soil reinforced by a group of floating columns. Considering the elastic strain in the surrounding soil and plastic strain in column, Castro (2016) developed a closed-form solution to estimate the settlement of small column groups. A mechanical model has been developed by Das and Deb (2014) to study settlement as well as

bending moment and shear force of the raft foundation resting on a stone column improved ground.

Load-deformation behavior of a plain footing is a complex phenomenon where three types of deformation mode have been observed, i.e. strain hardening, strain softening and limiting capacity. With the inclusion of stone columns, the complexity is further increased due to multiple failure modes that can happen in the improved ground system such as wedge shearing, bulging, and punching (Tan and Ng 2013). Prediction of the nonlinear behavior of the stone columns reinforced foundations is difficult except by numerical approach. However, this modern computational technique requires advanced constitutive model to simulate the soil and the column behavior where the soil/column properties are sometimes difficult and expensive to obtain.

In previous study, a simplified design approach was developed to predict the long term drained settlement of a stone columns supported foundation. It was first compared against a series of finite element analysis where a good match was obtained for the load-deformation curve (Ng et al. 2014). In this study, the soundness of the design approach was further tested against a laboratory model test and a field test.

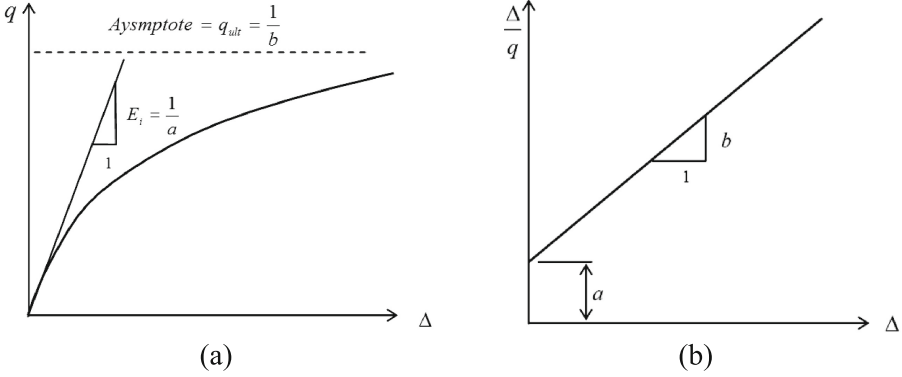
## 2 Simplified Design Approach

The general hyperbolic equation has been used to simulate this nonlinear stress-strain response of soils (Kondner 1963; Duncan and Chang 1970). Jeon and Kulhawy (2001) further adapted the hyperbolic equation to displacement and the equation is given below:

$$q = \frac{\Delta}{a + b\Delta} \quad (1)$$

where  $q$  is the applied bearing pressure,  $\Delta$  is the footing displacement, and  $a$  and  $b$  are curve fitting parameters. The curve fitting parameters can be obtained by plotting the actual load-deformation curve in a linearized hyperbolic form as shown in Fig. 1 where  $a$  is the intercept of  $\Delta/q$  versus  $\Delta$  plot while  $b$  is the slope of  $\Delta/q$  versus  $\Delta$  plot. The parameter  $a$  is the inverse of initial tangent modulus of the ground while parameter  $b$  is related to the inverse of ultimate bearing capacity,  $q_{ult}$  of the footing system. The ultimate bearing capacity and the actual failure stress are assumed to be the same since the footing drained performance usually exhibit strain hardening behavior.

Footing supported by stone columns displays stiffer response under load as well as having a higher ultimate bearing capacity compared to a plain footing which also means smaller values for  $a$  and  $b$  parameters in the Eq. (1). The term ‘plain footing’ is used to refer to the un-reinforced shallow foundation. The determination of  $a$  and  $b$  parameters for improved ground is the essence of this new design approach. These two curve fitting parameters acquired from the load-deformation curve for a plain footing in drained manner is needed in the first place. Then, reduction factor,  $M$  applies to these parameters to obtain the hyperbolic curve for the reinforced stone column foundation, give as:



**Fig. 1.** (a) Hyperbolic stress-strain curve; (b) Transformation of hyperbolic relation.

$$\begin{aligned} a_1 &= \frac{a}{M} \\ b_1 &= \frac{b}{M} \end{aligned} \quad (2)$$

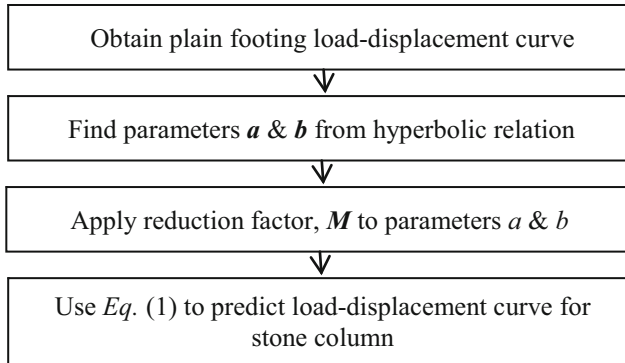
which they are named as modified  $a$  and  $b$  parameters for stone columns reinforced foundation. Modified parameters are dependent on two factors: area ratio,  $\alpha$  and column length,  $L$ . Area ratio is defined as the ratio of stone columns cross sectional area to the cross sectional area of the footing. Reduction factor,  $M$  is proposed as:

$$\begin{aligned} M &= 1 + \frac{L}{L_{opt}}(2\alpha - 0.15) & L \leq L_{opt} \\ M &= 1 + \frac{L}{d}(2\alpha - 0.15) & L \leq d \end{aligned} \quad (3)$$

where  $d$  is the thickness of soft soil below footing,  $L_{opt}$  is the optimum length of stone column and  $L/L_{opt}$  and  $L/d$  are denoted as length ratio. Columns longer than a certain length which give no further improvement in settlement performance is termed optimum length,  $L_{opt}$ . The  $M$  value was first approximate from a series of parametric studies conducted during the preliminary study by means of axisymmetric finite element method using 15-node triangular element with elastic-perfectly plastic material for both columns and soils where  $M$  is taken to be equal to the basic settlement improvement factor,  $n_0 = 2.575\alpha + 0.931$  ( $n$  = the ratio of settlement without improvement over settlement with improvement) for cases with column length longer than the optimum length. However, further improvement was made to account for nonlinear behavior of soil, thus the  $M$  value becomes slightly smaller i.e.  $M = 2\alpha + 0.85$  for end bearing columns or columns longer than optimum length. This value is influenced by the area replacement ratio together with the length ratio and those are the important factors in determining the stone column performance. A previous study by Tan et al. (2014) suggested that the optimum length can be computed as:

$$L_{opt} (m) = (2\alpha + 0.8)D + 0.5 - t \quad (4)$$

where  $D$  equal to the diameter or breath,  $B$  of a footing, and  $t$  equal to the thickness of granular mat above the stone columns. The load-deformation curve for the stone column reinforced foundation can be drawn using Eq. (1) when the values of  $a_1$ , and  $b_1$  are obtained. The design procedure to predict the load-deformation curve for a small column group is summarized in Fig. 2.



**Fig. 2.** Calculation procedures in hyperbolic method

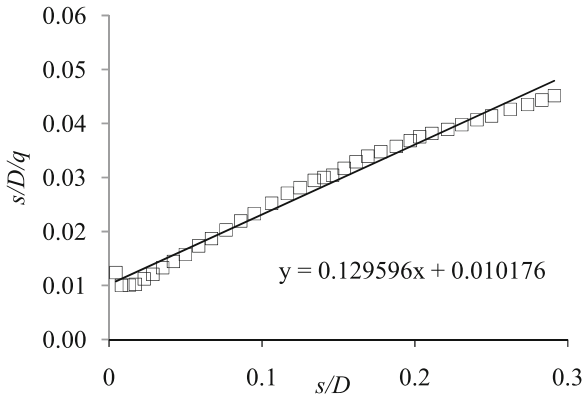
The simplified design approach differs from the conventional method because it does not require the arbitrary selection of soil parameters, but is capable of simulating the yielding response of the improved ground that is strain hardening. Besides, the effect of footing embedded depth, ground water table and soil layering are mooted in this design approach since the only requirement is the stress-strain characteristic of a plain footing under similar testing condition.

### 3 Validation with Model Test and Field Load Test

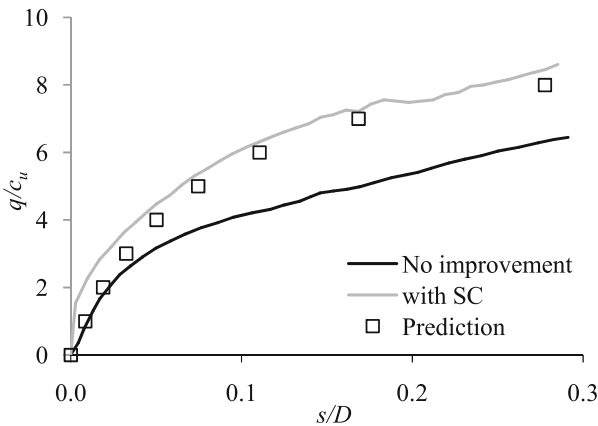
#### 3.1 Model Test (Wood et al. 2000)

In a model test by Muir-Wood et al., floating columns with the length,  $L$  of  $1.7D$  ( $>L_{opt} \approx 1.33D$ ) and  $\alpha = 0.24$  were used to support a rigid circular footing of 0.1 m diameter. The sand columns were formed with replacement technique and placed in a square grid extending just beyond the edge of the footing. The relative density of the sand poured into the columns was around 0.5. The undrained shear strength of the surrounding soil is  $C_u = 10$  kN/m<sup>2</sup>. The displacement controlled test was conducted slowly in a drained manner until 30 mm settlement was reached.

Figure 3 shows the hyperbolic relation of the plain footing without stone columns as used in the model test. The parameter  $a$  and  $b$  are obtained as 0.01 and 0.13 respectively. Using Eq. (3), the reduction factor  $M$  was computed as 1.33. The



**Fig. 3.** Hyperbolic relation.



**Fig. 4.** Load deformation results.

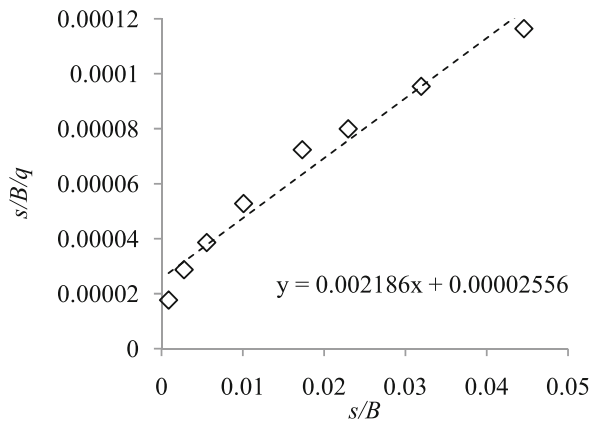
prediction is well comparable to the model test as depicted in Fig. 4 despite slight overestimation of settlements, especially in the beginning of loading stage. There are probably two reasons for this overestimation. First, the footings are not only supported underneath, but with extra “buttressing” columns outside the edge of the footing which give extra constraint effect. Second, the footing was contained in a tank with 300 mm diameter, thus the boundary is only 1.5 times the footing diameter measured from the centerline and this boundary effect may have influenced the footing performance.

### 3.2 Field Load Test (Stuedlein et al. 2011)

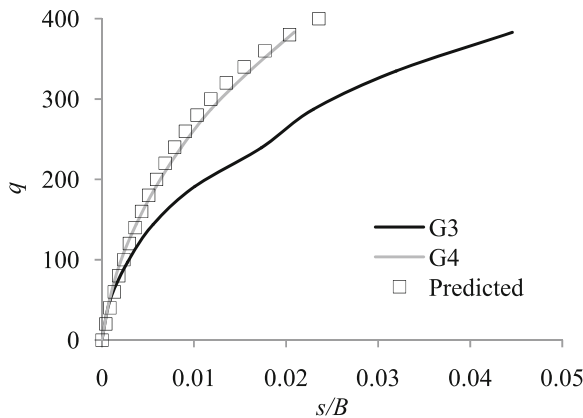
A field load test (denoted as G4) on square footings of 2.7 m width supported with 5 numbers of floating stone columns. The column length is 3.05 m which is shorter than the optimum length,  $L_{opt}$  of 4.34 m. The diameter of columns is 0.76 m and the area

replacement ratio,  $\alpha$  is 0.3. The stone columns in the test are vibro-compacted. The first soil layer is 0.7 m thick hard, desiccated clay crust, followed by soft to medium stiff upper clay layer to a depth of 3.7 m, overlying sandy silt/silty sand layer with total thickness of 0.7 m. 4.5 m deep onwards, lie the fourth and deepest layer which is a slightly silty clay. Laboratory soil tests showed the upper 4.5 m was over-consolidated. A plain footing test (G3) acted as control test. Square footings in both tests were placed on the ground surface, direct contact with stone columns. The duration of load tests was approximately 500 to 600 min (8.5 to 10 h).

Using the proposed method, the reduction factor,  $M$  was calculated to be 1.32. The result of field load test was compared with the result obtained from the proposed method where a good agreement was obtained as shown in Fig. 5. The slight over prediction may probably due to the short period of test which the drained condition had



(a)



(b)

**Fig. 5.** Field test (a) Hyperbolic relation, and (b) Load-deformation results.

not been fully achieved. In addition, the ultimate bearing capacity for the column group was predicted to be 602 kN/m<sup>2</sup>.

## 4 Conclusion

This paper presents a validation of a simplified design approach against a model test and a field load test where the results proved the method to be sufficiently accurate in estimating the drained settlement of stone columns supported foundation. The load-deformation response of the foundation can be characterized with hyperbolic function as shown in the above validation exercise. Albeit simple and easy, the method is indeed a rational method which has taken into account many intrinsic behaviors of stone columns such as the load sharing mechanism, nonlinearity and length ratio.

## References

- Babu, M.D., Nayak, S., Shivashankar, R.: A critical review of construction, analysis and behaviour of stone columns. *Geotech. Geol. Eng.* **31**(1), 1–22 (2013)
- Balaam, N.P., Booker, J.R.: Analysis of rigid rafts supported by granular piles. *Int. J. Numer. Anal. Methods Geomech.* **5**(4), 379–403 (1981)
- Bouassida, M., Jellali, B., Porbaha, A.: Limit analysis of rigid foundations on floating columns. *Int. J. Geomech.* **9**(3), 89–101 (2009)
- Bouassida, M., Carter, J.P.: Optimization of design of column-reinforced foundations. *Int. J. Geomech.* **14**(6), 04014031 (2014)
- Bouassida, M., Hazzar, L.: Performance of Soft Clays Reinforced by Floating Columns. In: *Ground Improvement Case-Histories: Embankments with Special Reference to Consolidation and Other Physical Methods*, p. 433 (2015)
- Castro, J., Sagaseta, C.: Consolidation around stone columns. Influence of column deformation. *Int. J. Numer. Anal. Meth. Geomech.* **33**(7), 851–877 (2009)
- Castro, J.: An analytical solution for the settlement of stone columns beneath rigid footings. *Acta Geotech.* **11**(2), 309–324 (2016)
- Das, A.K., Deb, K.: Modeling of uniformly loaded circular raft resting on stone column-improved ground. *Soils Found.* **54**(6), 1212–1224 (2014)
- Duncan, J.M., Chang, C.Y.: Nonlinear analysis of stress and strain in soils. *J. Soil Mech. Found. Div.* **96**(5), 1629–1653 (1970)
- Han, J., Ye, S.L.: Simplified method for consolidation rate of stone column reinforced foundations. *J. Geotech. Geoenviron. Eng.* **127**, 597–603 (2001)
- Jeon, S.S., Kulhawy, F.H.: Evaluation of axial compression behavior of micropiles. In: *Foundations and Ground Improvement*, pp. 460–471. ASCE (2001)
- Kondner, R.L.: Hyperbolic stress-strain response: cohesive soils. *J. Soil Mech. Found. Div.* **89**(1), 115–143 (1963). ASCE
- Lawton, E.C., Fox, N.S.: Settlement of structures supported on marginal or inadequate soils stiffened with short aggregate piers. In: *Geotechnical Special Publication 40*, pp. 962–974 (1994)
- Najjar, S.S.: A state-of-the-art review of stone/sand-column reinforced clay systems. *Geotech. Geol. Eng.* **31**(2), 355–386 (2013)

- Ng, K.S., Tan, S.A.: Design and analyses of floating stone columns. *Soils and Foundation* **54**(3), 478–487 (2014)
- Ng, K.S., Tan, S.A., Sun, J.: A new approach to the estimation of settlement and ultimate bearing capacity of stone columns supported shallow foundation. In: *The 8th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE 2014)*, 18–20 June 2014, Delft (2014)
- Priebe, H.J.: *The Design of Vibro Replacement*, pp. 31–37. *Ground Engineering* (1995)
- Rao, B.G., Ranjan, G.: Settlement analysis of skirted granular piles. *J. Geotech. Eng.* **111**, 1264–1283 (1985)
- Shahu, J.T., Reddy, Y.R.: Estimating long-term settlement of floating stone column groups. *Can. Geotech. J.* **51**, 770–781 (2014)
- Stuedlein, A.W., Holtz, R.D.: Analysis of footing load tests on aggregate pier reinforced clay. *J. Geotech. Geoenviron. Eng.* **138**(9), 1091–1103 (2011)
- Tan, S.A., Ng, K.S.: Stone columns foundation analysis with concentric ring approach. In: *Proceedings of the Third International Symposium on Computational Geomechanics (ComGeo III)*, Krakow, Poland (2013)
- Tan, S.A., Ng, K.S., Sun, J.: Column groups analyses for stone column reinforced foundation. *Geotechnical Special Publication 233*, pp. 597–608 (2014)
- Wood, D.M., Hu, W., Nash, D.F.T.: Group effects in stone column foundations model tests. *Geotechnique* **50**(6), 689–698 (2000)