Estimation of Modular Ratio and Modulus of Deformation of Granular Piles from in Situ Compression Tests Under Direct Loading

M. Najamuddin, M. R. Madhav, and V. Padmavathi

Abstract Granular piles have been and continues to be used extensively for improving the ground in terms of increased load carrying capacity, reduced settlements, for rapid dissipation of pore pressures, to mitigate liquefaction effects etc. The effective application of granular piles in soft ground necessitates the knowledge of deformation parameters of the ground and of the granular piles, for determining the behavior of granular piles in different soil conditions. This paper presents a method to estimate the modular ratio of granular piles and modulus of deformation of surrounding in situ soil from the load—settlement response obtained from the compression tests. The direct loading test cases in which the applied load is totally transferred onto the granular pile have been considered in this study.

Keywords Soft ground · Granular piles · Load tests · Settlement influence factor · Modulus of deformation · Modular ratio

1 Introduction

Granular Piles are often used as a ground improvement measure, and are very effective in increasing the load carrying capacity and contribute to reducing the settlements of the ground. Granular piles can usually be constructed using vibro-flotation or ramming techniques. Granular piles are often provided in groups to engineer large areas of ground.

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The implementation of theoretical solutions to practical problems require sufficient knowledge of the shear and deformation parameters of the soil and granular piles. According to Poulos and Davis [1], the deformation parameters of soil can be determined from laboratory triaxial tests, full-scale load tests, and/or empirical correlations based on previous experiences. The results obtained from the small-scale laboratory tests may comprise of limitations and do not reflect the actual in situ conditions to determine the true in situ parameters. Hence, interpretation of in situ load tests is a better alternative to determine the deformation parameters.

Mattes and Poulos [2] employed linear elastic theory to analyze the behavior of a compressible floating pile of circular cross-section in an ideal elastic soil mass. Pile displacements are expressed conveniently in terms of dimensionless influence factors. Sharma [3] presented analysis of a single granular pile considering both vertical and radial displacement compatibility. Gupta and Sharma [4] considered the non-homogeneity of granular piles for the settlement analysis. Prasad and Madhav [5] presented a parametric study to quantify the percentage of load transferred on to the granular pile as a function of the relative sizes of the granular bed and the rigid plate with respect to the diameter of the granular pile, and relative stiffness of the granular pile with respect to that of in situ soil.

Fatahi et al. [6] proposed a method to determine the deformation modulus of granular pile using numerical simulation. Initially, deformation parameters were assumed in the finite element modelling and the numerical simulation results were compared with in situ test results. The deformation modulus of the granular pile was obtained iteratively based on the accuracy of prediction. In the proposed method, the settlement influence factors given by Mattes and Poulos [2] for a single compressible pile have been utilized in the back analysis for deformation parameters of granular piles and the ground.

2 Methodology

A compressible pile of length, L, and diameter, d, is installed in in situ soil which has modulus of deformation, E_s, and subjected to an applied axial load, P, as shown Fig. 1(a) Mattes and Poulos [2] expressed the settlement of compressible pile, S, shown in Fig. 1(a) by Eq. (1).

$$S = \frac{P}{E_s L}.I_p \tag{1}$$

where I_p is settlement influence factor and depends on the length to diameter (L/d) ratio and the modular ratio (K) of the granular pile.

The relative stiffness or modular ratio of the granular pile is defined as the ratio of modulus of deformation of granular pile to that of the in situ soil ($K = E_{gp}/E_s$). A general load test on granular pile consists of loading arrangement as shown in

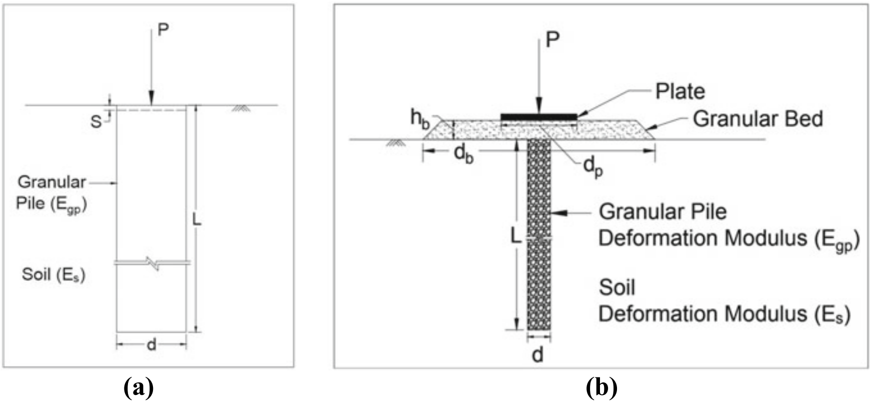


Fig. 1 **a** Settlement of compressible pile under axial load **b** Definition sketch for a load test

Fig. 1(b), which includes granular bed of diameter, d_b and thickness, h_b, underneath a test plate of diameter, d_p. The proportion of load transferred to a granular pile through a granular bed depends on the relative sizes of granular bed and test plate involved as discussed in Prasad and Madhav [5]. The entire applied load transmits to the pile, if the test plate and granular bed are of the same diameter as that of the granular pile in presence of granular bed and the test plate diameter is same as the pile diameter in absence of granular bed.

The soil deformation modulus, E_s, is evaluated from Eq. (2), by rewriting Eq. (1) in terms of E_s, in which the estimation of E_s requires knowledge of I_p which is a function of K. The length and diameter of the pile, applied load and settlement are obtained from load test details. Hence, as E_s and I_p are unknown in Eq. (2), the modular ratio is assumed, in order to determine I_p and estimate E_s.

$$E_s = \frac{P I_p}{S L} \tag{2}$$

The settlement influence factor, I_p, is obtained based on L/d and modular ratio, K, from Mattes and Poulos [2] as presented in Fig. 2. The settlement influence factors given by Mattes and Poulos [2] ranges from K = 10 to 100, the I_p values with respect to L/d have been interpreted by extrapolating the curves for K = 5 and presented in Fig. 2. I_p is independent of K for an L/d of 5 and for higher L/d, it decreases with increase in modular ratio.

The following steps are proposed to estimate the modular ratio and deformation modulus of granular piles:

1. The settlement and applied load are to be obtained from load–displacement curve of compression test on pile of known length and diameter. The settlement influence factor is to be obtained from Fig. 2, for an assumed modular ratio and known L/d.

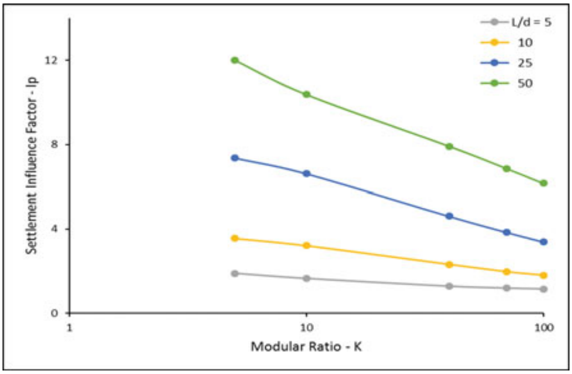


Fig. 2 Settlement Influence factors versus Modular Ratio for L/d = 5 to 50 and Poisson's Ratio of 0.5

2. Deformation modulus of in situ soil, E_s, is to be estimated from Eq. (2) using the parameters in step-1.
3. A plot is to be drawn between E_s and assumed range of K (5–100).
4. A range of soil deformation modulus based on the type of soil present is to be drawn on the same plot.
5. The K versus E_s curve plotted in step-3 is to be used to determine the modular ratio of granular pile from the K values corresponding to the E_s range from step-4.
6. Finally, the range of deformation modulus of granular pile, E_{gp}, is determined based on the E_s and modular ratio K obtained from step-4 and 5 respectively.

3 Case Studies

The present analysis is carried out by collecting data from different case studies of compression test on granular pile. These individual test details are described in Sects. 3.1, 3.2 and 3.3.

3.1 Case Study 1

Hoque and Alamgir [7] studied the behavior of granular pile of 8.5 m length and 0.3 m diameter which were constructed using the rammed-displacement method at the KUET campus, Khulna, Bangladesh. Three load tests were carried out, one on natural soil, second and third on granular pile after one month and one year of installation respectively, to analyze the granular pile behavior and performance with time. A granular pile was tested with a 0.3 m diameter plate which is same as diameter of the pile by placing the plate directly on the pile, without granular bed under the plate. The load displacement response of the three tests are illustrated in Fig. 3(a).

The soil profile existing in site is shown in Fig. 3(b) and the layers are listed from ground level to 18 m depth starting with silty sand followed by clayey silt and organic clay. E_s is estimated for an applied load of 28 kN and corresponding settlement of 3.3 and 4.3 mm for one month and one year respectively from Fig. 3(a).

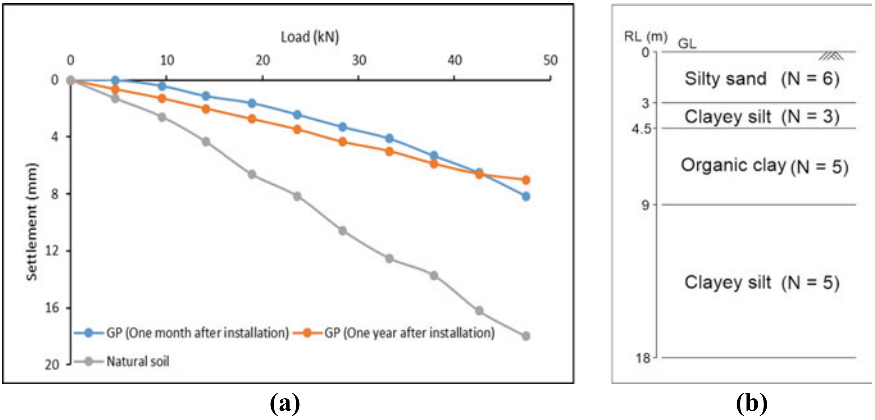


Fig. 3 **a** Load—Displacement plot from case study 1 **b** Soil profile—case study 1

3.2 Case Study 2

Bhosle and Vaishampayan [8] carried out load test on a granular pile of 20 m length and 0.9 m diameter, intended to improve the ground conditions for the construction of a container yard at Vallarpadam Island, Cochin, India. These granular piles were constructed using the vibro-replacement method. MS plate of 0.9 m diameter upon a 100 mm sand blanket layer was used in the test. The load settlement response is presented in Fig. 4(a). The settlement and applied load considered, in the estimation of E_s, are 4.2 mm and 230 kN respectively from Fig. 4(a). The subsurface stratification included layers of silty sand with shells, soft clay and fine sand as depicted in Fig. 4(b). The diameter of the sand blanket and the plate used in the test are same as that of the granular pile. Hence, the entire load applied on the plate was considered to be transferred onto the granular pile as the thickness of the sand blanket is less.

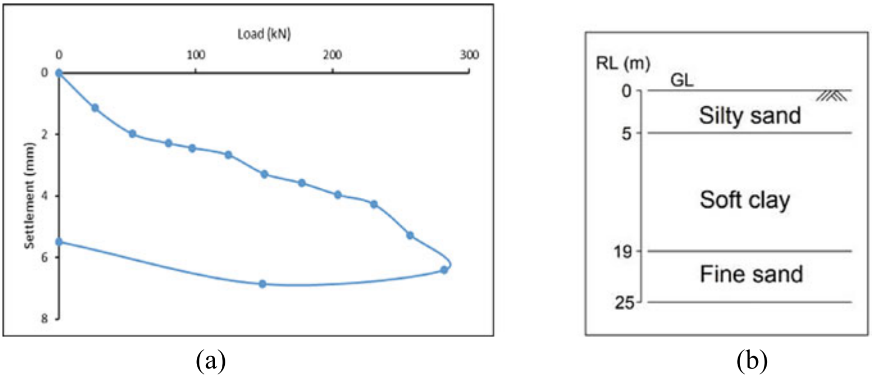


Fig. 4 **a** Load—displacement plot from case study 2 **b** Soil profile—case study 2

3.3 Case Study 3

Plate load test was carried out by Mokhtari and Kalantari [9] on granular pile constructed at four different locations (North, South, East, and West) of the site which was located at Bandar Abbas, Iran. The length and diameter of the pile were 12 and 0.8 m respectively. The plate size used for the test was 0.6 m diameter which was directly placed on the pile and the entire load applied is transferred onto the pile. The load displacement response and the soil profile are illustrated in Fig. 5a, b respectively. The applied load considered, in the estimation of E_s, from Fig. 5a for the South case is 12 kN for settlement of 2.3 mm.

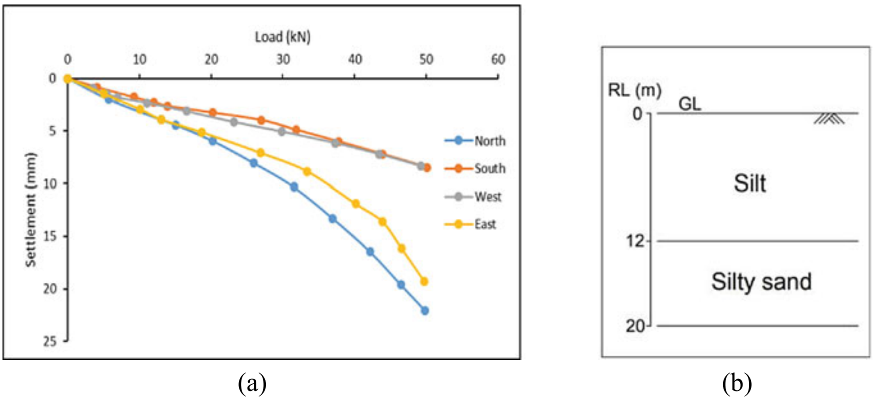


Fig. 5 **a** Load—displacement plot from case study 3 **b** Soil profile—case study 3

4 Results and Discussion

The estimated E_s for all the case studies is presented in Table 1 for the assumed modular ratio of 5–100. Table 2 presents the obtained deformation parameters of granular piles for the E_s range based on type of soil (Geotech Data [10]). The weighted average of E_s values along the length of granular pile has been considered by giving higher weightage to the top layer, if soil is stratified.

Table 1 Estimated Modulus of Deformation of Soil

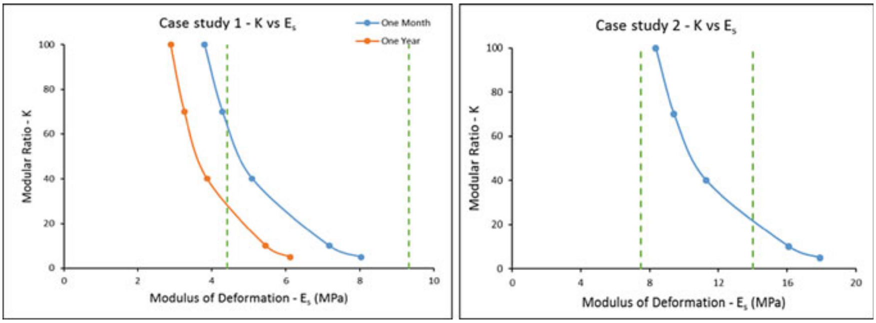
Assumed modular ratio–K	Estimated soil deformation modulus–E_s (MPa)						
	Case study 1		Case study 2	Case study 3			
	Undrained	Drained		North	South	West	East
5	8	6.1	17.9	1.4	2.1	1.6	1.3
10	7.2	5.5	16.1	1.2	1.9	1.4	1.2
40	5.1	3.9	11.3	0.9	1.4	1	0.9
70	4.3	3.3	9.4	0.7	1.1	0.8	0.7
100	3.8	2.9	8.3	0.7	1	0.8	0.6

Table 2 Estimated Deformation Parameters of Granular Pile

Case study		E_s range based on type of soil (MPa)	Modular ratio–K	Deformation modulus of GP–E_{gp} (MPa)
1	Undrained	8–4.4	5–64	40–281.6
	Drained	6.1–4.4	5–28	30.5–123.2
2		14–8.3	22–100	308–830
3 (South)		2.1–1.5	5–31	10.6–46.5

4.1 Results–Case Study 1

The variation of soil deformation modulus with assumed modular ratios is plotted in Fig. 6(a) for the tests performed after one month and one year of installation as described in case study 1. The one-month and one-year behavior of the ground is expected to reflect an undrained and a relatively drained condition respectively. The deformation modulus varies from 8 to 3.8 MPa for the undrained condition and 6.1–2.9 MPa for the drained condition, for a modular ratio range of 5–100, as indicated in Table 1. The undrained E_s is greater than the drained E_s throughout the range of K for the same load-settlement response. Based on soil stratification—silty sand, clayey silt and organic clay, the E_s range from Geotech Data [10] is 4.4 to 9.3 MPa which



(a) (b)

Fig. 6 **a** Variation of E_s with K for case study 1 **b** Variation of E_s with K for case study

is depicted in Fig. 6(a). The modular ratios obtained within this range, as presented in Table 2, for the undrained and drained conditions is 5–64 and 5–28 respectively. Hence, the granular pile deformation modulus is 40–281.6 MPa and 30.5–123.2 MPa for the undrained and drained condition respectively.

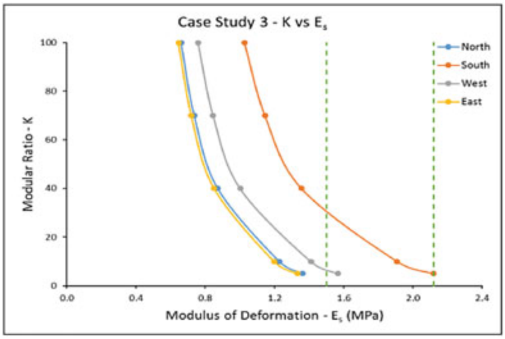
4.2 Results–Case Study 2

The soil deformation modulus for case study 2 is depicted in Fig. 6(b) which varies from 17.9 to 8.3 MPa for modular ratio of 5 to 100. An E_s range from Geotech Data [10] based on soil layers present—silty sand with shells, soft clay, and fine sand, which is 7.5–14 MPa. The modular ratio obtained from Fig. 6(b) for an E_s range of 14–8.3 MPa is 22 to 100 and the modulus of deformation of the granular pile (E_{gp}) obtained is 308–830 MPa.

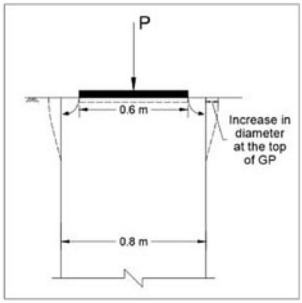
4.3 Results–Case Study 3

The results for all the load tests involved in case study 3–North, South, West, and East are illustrated in Fig. 7(a). The estimated soil deformation modulus, for the load test conducted at the south side of the site, is 2.1–1 MPa for a modular ratio range of 5–100 respectively. The E_s range for silt from Geotech Data [10] is around 1.5–6 MPa. Hence, for the South side of the site, for an E_s of 2.1–1.5 MPa, the modular ratio from the Fig. 7(a) is 5 to 31 and the corresponding granular pile deformation modulus is 10.6 to 46.5 MPa as presented in Table 2.

The estimated soil deformation modulus in this case study tends to be lesser than the range of the E_s based on the type of soil. This might be due to the diameter of the plate (0.6 m) used for the load test being less than the granular pile diameter (0.8 m).



(a)



(b)

Fig. 7 **a** Variation of E_s with K for case study 3 **b** Case study 3 loading arrangement

As there is no confinement for the granular pile, due to the smaller plate size, on the application of load there might be squeezing out of granular pile material which increases the diameter at the top of the pile (Fig. 7(b)) and this affects the settlement influence factors. If the diameter at the top of the granular pile does not increase due to the squeezing out of pile material, then the influence factors will tend to be higher which in turn results in higher E_s values.

5 Conclusion

Efficient ground improvement using granular piles requires understanding of its settlement behavior. This settlement prediction depends on the deformation parameters of ground and granular piles. The method proposed in this study, aims to estimate the deformation parameters which reflect the actual in situ behavior of the reinforced ground. The design of granular pile can be enhanced by estimating the deformation modulus of the granular pile. The proposed method was validated using different case studies and it indicated that this method can be applied to back analyze deformation parameters from in situ load tests which helps in predicting the accurate settlement of granular piles.

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