SOFT SOIL REINFORCED WITH GRANULAR PILE-MAT SYSTEM: ANALYSIS AND MODEL TESTS

By

Y. RAMANA REDDY

Submitted

In fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

HAUZ KHAS, NEW DELHI-110 016

INDIA

OCTOBER 2009

To
My Parents

CERTIFICATE

This is to certify that the thesis entitled "**SOFT SOIL REINFORCED WITH GRANULAR PILE-MAT SYSTEM: ANALYSIS AND MODEL TESTS**" being submitted by **Mr. Y. Ramana Reddy** to the **Indian Institute of Technology Delhi** is record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

Dr. J. T. Shahu

Associate Professor

Department of Civil Engineering
Indian Institute of Technology Delhi
New Delhi – 110 016
INDIA

ACKNOWLEDGEMENT

On the completion of this work, it is my pride and privilege to express my deepest gratitude with great appreciation to my supervisor, **Dr. J.T. Shahu** for his irreplaceable encouragement, inspiring guidance, keen interest, unfailing support and constant encouragement throughout this study. A person of myriad skills, he eased the way of my work by his wonderful contribution. His volunteered hours of valuable time helped me to put my best foot forward in right direction. His vast knowledge and experience on the subject made this study possible and even, more enjoyable.

My sincere thanks to Dr. K.K. Gupta, former Geotechnical Laboratory Incharge, IIT Delhi for providing me with necessary testing facilities and other related infrastructures required for conducting my research work in time.

I would also like to thank Prof. K.G. Sharma, Dr. G.V. Ramana, Prof. Manoj Datta, Prof. J.M. Kate, Prof. Subba Rao, Prof. B. Bhattacharjee and Dr. R. Ayothiraman for the useful discussions.

I am thankful to Soil and Rock mechanics laboratory staff namely, Mr. Manoj Kumar, Mr. D.S. Gosain, Mr. D. Biswas, Mr. Neeraj Gupta, Mr. Jodhraj Meena and Mr. Munni Lal for their help in conducting the experimental work.

I thank Mr. Ram Kumar and Mr. K.K. Bali, the workshop staff, for their help in the fabrication of model steel tank.

I also thank Mr. Amit Goswami and Mr. Prahlad Yadav, the project assistants, for their help in laboratory testing work.

My special thanks to all my friends Dr. Hanumanthu Rao, Dr. Mallikarjuna, Dr, Raveendra Babu, Dr. Ranga Rao, Dr. Ravi Shankar, Mr. Ganesh, Mr. Sai Ram, Mr.

Kondrai, Mr. Arvind Jain, Mr. Janaki Ramaiah, Mr. Maheedhar, Mr. Kausar Ali, Mr. S. Patra, Mrs. Somya, Mr. Singi Reddy, Mr. Krishna Kishore, Mr. Ravi Kumar Reddy, Mr. Sarvesh, Mr. Siva Reddy, Mr. R.K.Reddy, Mr. Ramand, Mr. Praveen, Mr. Satya, Mr. Naresh, Mr. Vijay, Mr. Vittal, Mr. Kishore, Mr. Rama Rao, Mr. Chitti Babu, Dr. Nagaraju, Mr. Kiran, Mr. Vamsi Krishna Reddy, Mr. Kondrai, Mr. Jettu, Mr. Brama Reddy, Dr. V. Babu, Mr. Rakesh Reddy, Mr. Misra, Mr. Deepak Tripati, Mr. Kapil, Mr. Gyani, Mr. Bansal, Mr. Naveen, Mr. Satish, Dr. Selvaraj, Dr. Thingless, Dr. Arshad, Mr. N. Kiran, Mr. Ibraiam and all my fellow students.

Last, but certainly not the least, words alone cannot express my deepest gratitude for the constant support, understanding and love that I received from my wife during the tenure of this study that provided me the necessary impetus to work on this thesis.

(Y. Ramana Reddy)

ABSTRACT

Granular piles are one of the most commonly used ground improvement techniques worldwide. Granular piles, especially those constructed by vibration techniques, are now seen as environmentally and economically acceptable ground improvement method. Granular piles increase the bearing capacity of the soft ground and reduce total and differential settlements of the superstructures constructed on the soft soils.

The critical consideration for a single pile or a small group of granular piles is usually the immediate bearing capacity under a rapidly applied load.

On the other hand, it is usually the long-term drained settlement of large pile groups that is important. The group effect in pile groups of limited size, though increases the bearing capacity by transferring the applied stresses to deeper depths, gives rise to high concentration of stresses by allowing less spreading of the applied stresses in the surrounding soil. This results into a high long-term drained settlement in large pile groups.

Presently available methods for calculating long term settlement may be classified as either (i) simple, approximate methods which make simplifying assumptions or (ii) sophisticated methods based on finite element theory. All of these methods, however, are based on unit cell concept which assumes an infinitely wide loaded area reinforced with granular piles of a constant diameter and spacing. For stone column groups less than about 20 to 40 columns, the methods based on unit cell idealization are known to be overly conservative. Unlike in the case of the unit cell, the stress applied to a granular pile group of limited size spreads out laterally with depth into the surrounding cohesive soil. This spreading of stress leads to considerably smaller settlement in case of granular pile groups of limited size as compared to that of the unit cell. This settlement reduction is sometimes empirically considered by

using yielding boundaries of the unit cell in a two-dimensional finite element analysis. Moreover, these methods are applicable only for fully penetrating granular piles and not for floating piles.

In this thesis, non-dimensional charts are developed for computation of the long term, drained settlement of granular pile group-mat-soft soil foundation based on laboratory model tests and numerical analyses.

The laboratory tests are conducted on adequately instrumented small scale physical models of the granular pile group foundation. Fully drained, long term, load controlled tests are performed on the model foundation placed in slurry deposited samples. Effect of various group foundation parameters, such as the diameter, length, spacing and density of granular piles; soil physical state, etc. is evaluated.

The numerical analyses consist of three-dimensional, elasto-plastic, finite element analyses of the model and the prototype foundation system. The soft soil behavior is represented by the modified Cam-clay model while the granular pile and mat are represented by the Mohr-Coulomb model. The constitutive parameters are evaluated by triaxial tests on representative samples. The predicted results by numerical analyses are calibrated against the laboratory model test results. A detailed parametric study of the prototype group foundation is then carried out using the finite element analyses to evaluate the relative importance of various foundation parameters on the group response and develop design charts.

The three-dimensional finite element analysis was successful in predicting the model test results. However, the magnitude of induced stresses and settlement in the model tests should not be compared with the prototype group foundation owing to low initial geostatic stresses and consequently, low Young's modulus of granular material in the model.

Load settlement responses for some typical prototype granular pile group foundations are presented along with the corresponding responses for the unit cell and the single pile. Typical variations in the responses due to changes in various foundation parameters are also presented for all the three cases.

The major foundation parameters affecting the group response are area ratio, pile length, Young's modulus of pile, initial geostatic stresses and soft soil properties (λ, κ, M and past maximum consolidation stress σ_{vm}). The minor parameters are mat thickness, and angle of shearing resistance and dilatancy of the granular material.

As certain foundation parameters, namely, area ratio, pile modulus, pile length, initial geostatic stresses, past maximum consolidation stress and stress ratio M of soft soil increase, the stiffness of the granular pile-mat foundation increases. Consequently, at any given applied vertical load, the footing settlement decreases. On the other hand, as λ and κ decrease, the soil becomes stiffer and the settlement decreases.

In general, the settlement S_u of the unit cell is found to be higher than the single pile settlement S_1 and the group foundation settlement S_g. As the applied load approaches the failure load, the single pile and the group settlement increase sharply and become higher than the settlement of the unit cell. The single pile settlement is found to be smaller than that of the group settlement.

In the granular pile group foundation of limited size, the spreading of stress occurs similar to that in a homogeneous soil. However, the granular piles attract relatively higher proportion of the applied stresses as compared to the surrounding soft soil. The bulging of one pile is resisted by the bulging of the neighboring piles and in the process, the applied stress is transferred to deeper depths. This mechanism known as the group effect gives rise to higher stress concentration in the soft soil below the footing and consequently, higher settlement in the group foundation as compared to that in the single pile.

In the case of single pile, the absence of group effect leads to higher spreading of stress and consequently, lower settlement as compared to that in the group piles. The unrestraint bulging is also responsible for the lower settlement.

The unit cell represents the response when the group consists of infinite number of piles. The boundaries of the unit cell are rigid and unyielding giving rise to a complete stress transfer to deeper depths. There is no spreading of the stress and a minimal bulging of the pile. The higher stresses inside the unit cell lead to higher settlement as compared to the group piles.

The ratio of group settlement to single pile settlement S_g/S_1 increases as the number of piles increases. S_g/S_1 is expected to reach a constant value at large number of piles (approximately greater than 40). The data are compared with the range and average values recommended by FHWA (1983) on empirical basis. The average values in both cases compare well.

The ratio of unit cell settlement to group settlement S_u/S_g decreases as the number of piles increases. S_u/S_g is expected to reach the value of 1.0 at large number of piles (approximately = 70 to 80).

Charts are presented for the estimation of the long term drained settlement of granular pile group foundation. The estimation of the group settlement envisages first estimating the settlement of the corresponding unit cell or the single pile and then calculating the group settlement using S_g/S_1 or S_u/S_g charts. For the foundation structures or material properties for which the responses are not available, suitable interpolation or extrapolation is recommended.

CONTENTS