Study of Reinforced Granular Pad-Inclusion- Soft Clay System

M. R. Madhav
Professor of Civil Engineering, Indian Institute of Technology, Kanpur

N. Miura
Director, Institute of Lowland Technology Saga University

1. Introduction

Granular piles (GP)/ stone columns, are commonly adopted to reinforce soft soils. Along with lime/cement mixed piles, jet grouting methods (e.g. DJM), these inclusions increase the bearing capacity and reduce the settlements of the structures founded on the ground. Unlike the latter, granular piles facilitate the dissipation of excess pore pressures and are ideally suited for seismic areas and for rapid achievement of consolidation settlement. (Bergado et al., 1996) presents an excellent review of the method, its application, design principles, etc. The presence of the adjacent columns is shown (Greenwood, 1997) to provide confinement which pushes the transfer of load to greater depths. (Akdogan et al., 1997) presents data from testing a large (5 m2) plate on a group of stone columns.

2. Granular Pad

In most cases, before the installation of granular piles, the site requires laying of a granular bed or pad to form a working platform and often, to raise the ground level. The granular bed has a significant effect on the overall performance of the reinforced ground (Madhav et al., 1994). The interactions between the various components of the structure and the ground, viz. the type and extent of the load, the stiffness and the thickness of the granular pad, the length, stiffness, dilation and the spacing of the granular piles and the extent and deformation characteristics of the soft soil, are complex and need intense study. This paper presents an investigation of the contributions of the granular pad and the loading plate on the response of the treated ground.

3. Test Details and Procedures

3. 1 Sample Preparation

Reconstituted alluvial silt samples were prepared in the laboratory by the reconsolidation technique. The finer fraction which consists of mostly silt with a small percentage, about 10- 15%, of clay was thoroughly mixed with ordinary tap water and kept for at least 24 hours for moisture equilibration. The initial water content was in the range of 40 to 44% which is higher (1.17 to 1.3 times) than the liquid limit of the soil.

3. 2 Properties of the Soil

The soil was an alluvial deposit and has the following composition and index properties: Sand 10 to 12%; Silt 75 to 80% and Clay 10 to 15%; $w_1 = 33$ and $I_p = 15$. The compression index, C_c of the soil was 0.27 and the coefficient of consolidation ranged between 4.0 to 5.7 mm²/s. The undrained shear strength of the soil was in the range of 6 to 7 kPa.

3. 3 Test Set-Up

A cylindrical tank, 270 mm in diameter and 620 mm high was fabricated out of galvanised metal sheet. Steel strips, 30 mm wide, were welded on the outer periphery of the tank at regular intervals for strengthening the tank against lateral deformations. The inside of the tank was coated with a lubricant, and a polythene sheet was placed to minimise friction between the tank and the sample. The tank had an outlet to drain the water out. A 70 mm thick sand layer was laid at the bottom for drainage. Thin strips of filter paper were also placed on the inside of the tank over the polythene sheet to facilitate faster consolidation during the sample preparation stage. To decrease the interference effect of different tests being conducted on the sample prepared in the same tank, another set of larger size tanks of diameter 390 mm and 330 mm deep were fabricated out of GI sheets and used for subsequent test series.

3. 4 Sample Preparation

The slurry was pored into the tank in three stages. After each stage the surface was leveled and sector shaped filter papers were laid on each surface to accelerate consolidation. The filter papers permitted free drainage but did not contribute to the stiffness of the soil. A sheet of filter paper and about 15 mm thick sand layer were placed on the top of the slurry. A thin metal plate, 265 mm in diameter, was then kept on the sand layer. The slurry was left to consolidate under its own self weight for one to two days. The bottom one-way valve was kept open for draining the excess water. The average settlements during the sample preparation phase ranged between 110 to 120 mm, i.e. about 17% of the initial height.

3. 5 Loading

Vertical loads were applied to the sample at regular intervals by placing the weights on the top plate. The increments in the loads were 5, 10, 20, 40, 80 kg. The surface settlements were measured using three dial gauges, each with a travel of 50

mm and a least count of 0.01 mm. They were placed in a triangular pattern to monitor tilt. If any tilt was observed, the loads were repositioned. The next load increment was placed only after the rate of deformation reduced to a level of 1 division, i.e. 0. 01 mm per hour. The final load was maintained for a further period of 48 hours for the equalisation of residual pore pressures, if any. After equilibrating under the final load increment, unloading of the bed was carried out in the reverse order of loading for further testing.

3. 6 Granular Pile Material

Gravel was used to construct the granular piles. The particle size ranged between 2.36 to 4.75 mm. The angle of shearing resistance, ϕ', of the granular material measured in a strain controlled direct shear test, ranged between 38^0 to 43^0 for different relative densities.

3. 7 Installation of Granular Piles

In the present study, the granular piles were installed by the cased hole method of the rammed stone column procedure. A hole of the required diameter, 25 mm in the present case, was made by driving an open-ended pipe and removing the soil inside with the aid of a helical auger. Gravel was poured into the hole created in 3 to 4 lifts while withdrawing the casing pipe gradually Each layer was tamped uniformly few times with a rammer to densify the granular pile. After the installation of the granular pile, it was rammed once again as a sort of preloading. A layer of sand was spread on top.

The installed diameter of the granular pile was observed to be slightly larger than that of the casing pipe due to tamping of the granular pile material. The final diameters of the granular piles ranged between 27 to 30 mm. Surface heave of about 5 to 10 mm was also noted because of the displacement of the soil surrounding the pile material during installation.

4. Load Tests

A series of model plate load tests were then conducted on the granular pile - soft soil system. The footing sizes were 25, 50 and 100 mm in diameter. Load is applied through a self straining load frame and in stages. The settlement of the footing plate was measured once again, with dial gauges with a least count of 0.01 mm. Three series of four load tests were carried out. Each series consisted of the following tests: (i) 25 mm dia. plate on unreinforced ground (UPLT); (ii) 25 mm dia. plate on a single GP (SPLT); (iii) 50 mm dia. plate on a
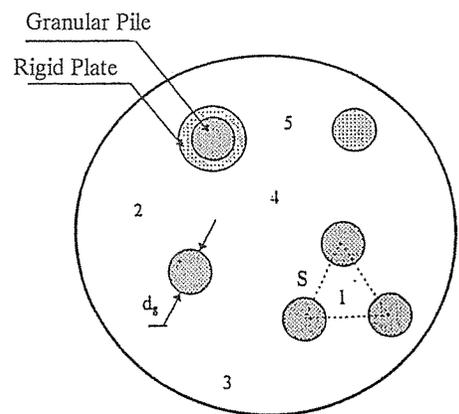
Fig. 1   Locations of Load Tests and Water Content Profiles

single granular pile (PRLT); and (iv) 100 mm dia. raft on a group of 3 GPs (GPLT) spaced at 75 mm (3 times the nominal diameter of the GPs). The locations of the various tests and for water content determinations are shown in Fig. 1. The top surface of the tank is divided into four quarters and each quarter is utilised for one test to minimise the effects due to variations in different samples, even though prepared identically.

4. 1　Post - Test Observations

After the load tests, the sample is dismantled and large number of water content determinations made at locations shown in Fig. 1. Differential settlements of the order of 2.5 to 5.0 mm were observed in almost all tests, possibly due to side friction on the inner surface of the tank. The undrained shear strength was also measured with a pocket vane shear apparatus to be in the range of 5 to 10 kPa.

The granular pile material and the soil were excavated and removed gradually after each test, to determine the diameter of GP at 20 mm depth intervals.

4. 2　Tests in CBR Moulds

A second series of tests were carried out in the relatively smaller size CBR molds (dia. 150 mm and height 230 mm). After the slurry was poured in and the top plate placed, the sample was left for one day to consolidate under self weight. Subsequently, it was transferred to a motorised loading frame in which the load could be applied by moving the set up at a very slow and constant strain rate as in a drained triaxial test. At the end of the day, the machine was switched off to permit equalisation of residual pore pressures and the loading commenced from the following morning. After the required stress level was attained, the set up was removed from the machine and dead weights that provide the same level of stress as the consolidation stress in the loading frame, were kept on top of the loading plate and the settlements monitored as a function of time as in the case of the large diameter tank. Unloading at the end of final consolidation and the procedure for the installation of GPs, was the same as described above.

In this test set up, the effect of the top plate diameter on the load - settlement response of the GP- Soil system was studied. The plate or footing sizes were 25 mm to test the single granular pile and 50 and 75 mm to investigate the effect of the raft diameter. In another series, instead of a
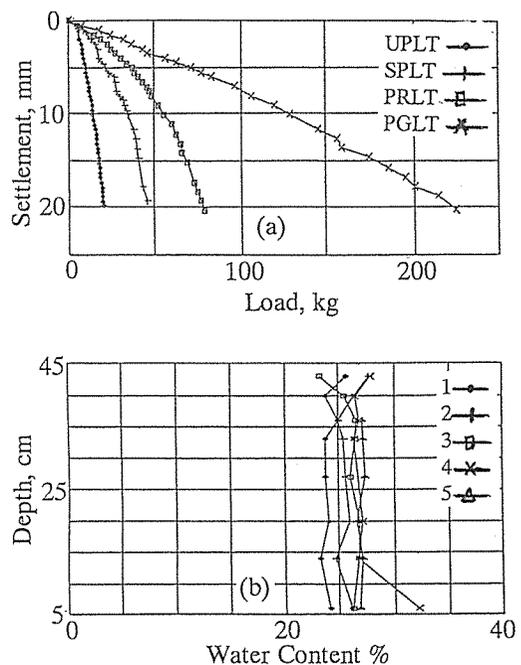
Fig. 2　Settlement vs Load (a) and Water Content with Depth (b) Series II

fully penetrating granular pile (L/H=1.0), partially penetrating (L/H=0.8) piles were installed and tested for the same sizes of top plates. L and H are the length of the GP and the thickness of the soft soil respectively.

5. Results and Discussion

Three series of tests were carried out in the tank of size 270 mm (dia.). In each series, load tests on untreated ground (UPLT), on a single granular pile (SPLT), on a granular piled-raft (PRLT) and a raft on a group of three granular piles (PGLT) were conducted. The typical load-settlement relations and the water content variations with depth after the test are presented in Fig. 2. The loads corresponding to a displacement of 20 mm were 20.0, 45.5, 87.3 and 225.5 kg for the four tests UPLT, SPLT, PRLT and PGLT. The ultimate values by the double tangent method for the first three tests are 5.45 kg, 24.5 kg and 45.5 kg respectively. Based on the undrained bearing capacity is calculated as 11.1 kPa, the predicted capacity of the granular piled-raft is 40.9 kg giving an efficiency of 1.02. The water contents ranged between 24 and 27% with an average of 26%. It has been generally observed that the water contents of points closer to the granular piles were smaller as expected than elsewhere thereby confirming the fact that granular piles did drain the soil.

The load - displacement relations for the raft on groups of three granular piles consistently exhibit a much better response in all the three series of tests, particularly at small displacements. The loads for single and three pile groups at a displacement of 5 mm are 21.8 and 70.9 kg respectively. The piles in a large group appear to carry more load than three times the load on a single pile because of the additional confining stresses mobilised by the larger diameter raft or footing. The stresses transferred to the soil by a larger diameter footing increase the confining stresses on the granular pile over a greater depth, thereby increasing its modulus and the carrying capacity. A similar order of increases in the loads carried by the three pile group can be noted at a raft displacement of 10 mm, the loads for single and three pile groups being 34.5 and 127.3 kg. This phenomenon is in variance to the one reported for rigid pile groups (Poulos et al., 1980) in which due to the interference effect the displacements of piles in a group for the same load as on a single pile, are more than that of a single pile.

5. 1 Effect of Raft Size

The load - settlement responses of a single granular pile with raft or top plate diameters of 25, 50 and 75 mm are presented in Fig. 3 for fully (L/H=1.0) penetrating GP. Results for plate size of 25 mm correspond to the response of the granular pile alone while the larger plates provide
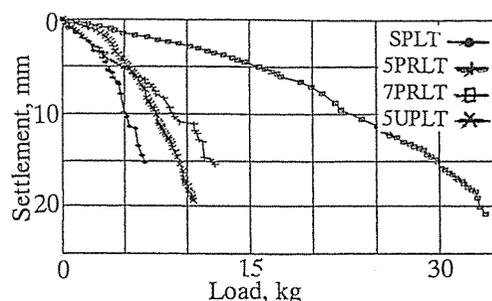

Fig. 3 Load vs Settlement: Test in CBR Mould- Fully Penetrating GP

the interaction effect due to the restraint offered by the loads from the plate area which is outside the pile diameter. The responses of the granular piled rafts with plate sizes of 50 and 75 mm are much improved compared to that of the pile tested alone. A single granular pile carries a load of 3.5 kg at a displacement of 5 mm. The corresponding loads for the piled rafts with 50 and 75 mm plates on top are 5.5 and 15.5 kg respectively. The larger the plate size, the higher is the load carried by the granular pile due to stress transfer to the soil surrounding the granular pile, and deeper is its effect in confining the pile.

5. 2 Effect of Granular Pad

The series of tests carried out in the larger diameter tank (d = 390 mm and H = 330 mm) investigate the effects of the granular pad and that of the loading plate on the granular

Fig. 4   Settlement vs Pressure–Series IV

Fig. 5   Settlement vs Pressure– Series V

pile reinforced soil. The length to diameter ratio of the granular pile in this case is about 9.5. Two thicknesses, 25 and 12.5 mm of the granular pad were used corresponding to thickness to GP diameter ratios of 1.0 and 0.5. While the plate size for the single GP was 25 mm, plates of 50 mm was used to test untreated and piled raft. The three pile group was tested with 75 mm dia. plate. Figure 4 presents the stress versus settlement responses of untreated ground, single granular pile and the piled raft with a granular pad thickness of 25 mm. Unlike in the previous series of tests, the footing on the untreated ground exhibits local shear failure, the initial curve being steep and the final or ultimate stress being reached asymptotically. The single granular pile loaded through a plate of the same size as the GP, exhibits a large linear stress – settlement response and a gradual change of curvature. The response of the granular piled raft is intermediate to the above two curves and combines the characteristics as expected. The bearing capacities for the three cases have been estimated by the
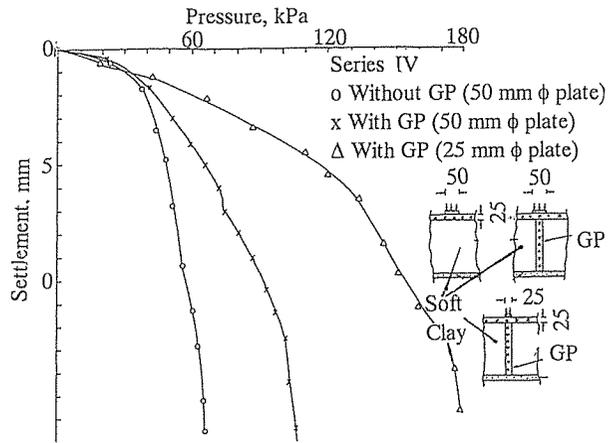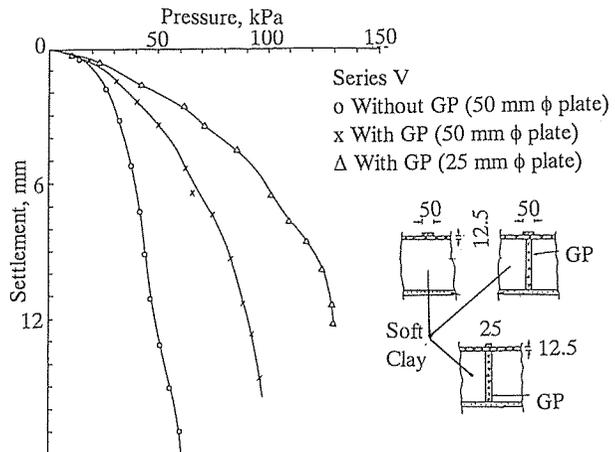
double tangent method as 40.3, 113.3 and 52.15 kPa respectively. The efficiency of the piled raft works out to 89.1%. The slopes of the curves appear to be of the same order for the three tests considered.

Results of series of tests carried out with a granular pad thickness of 12.5 mm, show (Fig. 5) a remarkable and consistent decrease in the ultimate bearing capacities. The values are 27.1, 108.2 and 39.4 kPa for the footing on untreated ground, single granular pile and the piled raft respectively. Reduction of granular pad thickness from 50 to 25 mm (h/d ratio of 1. 0 to 0.5) decreased the bearing capacities by 32.7%, 4.5% and 24.4% respectively. The effect of the thickness of the granular pad on the single granular pile is marginal as the load is directly transferred to the stiff pile directly and not to the surrounding soil. The efficiency of the granular piled raft in this case is 91%, slightly more but of the same order as that for the thicker granular pad.

Results for the rafts on three pile groups with 50 and 25 mm thick granular pads (Fig. 6) clearly illustrate the significant effect of the pad. The curve for the former case is consistently steeper than that for the thinner granular pad. Both the initial stiffness and the ultimate bearing

Fig. 6 Responses of Three (Gran.) Piled Rafts–Series IV & V

Fig. 7 Deformed Shapes of GPs–Series IV

capacity of the foundation are larger for the thicker granular pad. Increasing the relative thickness of the pad from 0.5 to 1.0 times the granular pile diameter, increases the ultimate bearing capacity from 61.2 to 73.5 kPa, an increase of 20%. Therefore, while analysing the results of granular pile reinforced ground, the contribution from the granular pad should not be ignored.

5. 3 Deformed Shapes of the Granular Piles

Typical shape of the GP was measured (Fig. 7) after the completion of the load testing by removing or scraping the soil carefully in small steps and measuring the exposed diameter of the granular pile. It is commonly reported (Greenwood, 1970 and Hughes, 1975) that stone columns bulge at a depth of about one to one and half
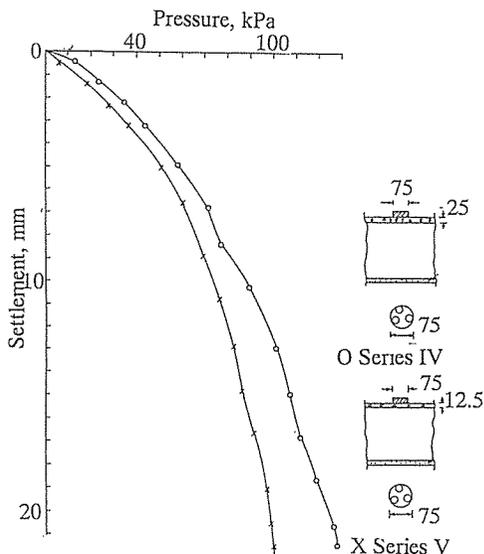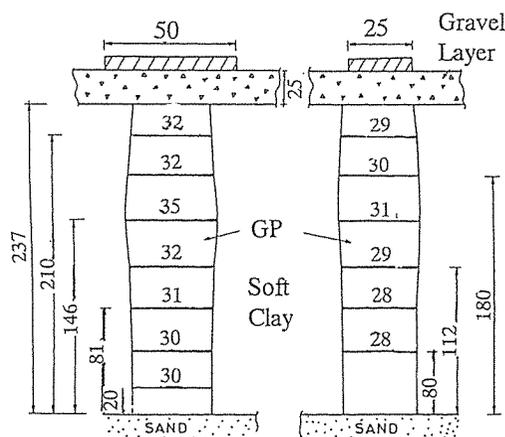
diameters from the top if tested in isolation. In the present series of tests with 25 mm thick granular pad on top, bulging of granular pile tested with a plate of 25 mm dia., took place in the depth range of 57 to 60 mm while under a 50 mm diameter plate, the bulging seems to have extended into a somewhat deeper depth of 57 to 120 mm. With a granular pad of thickness 12.5 mm, the bulging seems to have taken place at depths of 50 mm in case of plate of 25 mm on
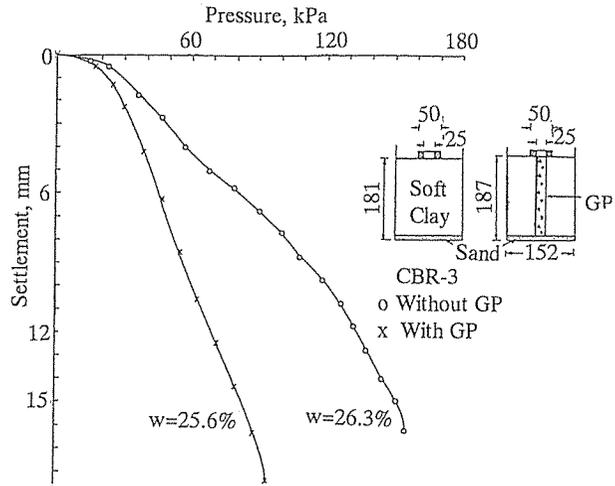

Fig. 8   Reinforcing Effect of GP on Soft Soil

single granular pile and 30 to 75 mm for a plate of 50 mm on granular piled raft. The length of the granular pile that has bulged out is more in case the granular pad is thinner. The wider the loading plate and thicker the granular pad, the deeper would be depth of bulging. The loading plate and the granular pad transfer the applied stress over larger areas near the surface. Larger the area at the surface, deeper would be the depths over which lateral stresses are generated in the soil which increase the confining stress on the pile and thus, reduce the tendency for bulging. Therefore to force bulging of the granular pile to greater depths and attain larger capacities, it is advisable to provide either a thicker or a stiffer granular pad on top.

5. 4 Reinforcing Effect of Granular on the Soft Soil

The reinforcing effect of the granular piles on the overall settlement response of the treated ground is well known. By virtue of their relative stiffness, the applied load arches onto the granular piles whose deformation modulus is at least one order higher than that of the in situ soil and hence the settlements get reduced to one third to one fourth the values for the untreated ground. On the other hand GPs stiffen the in situ soil by preventing lateral displacements of the soil surrounding them as well. In the presence of granular piles, the lateral deformations of the soil adjacent to the granular piles is reduced considerably because of their rela-
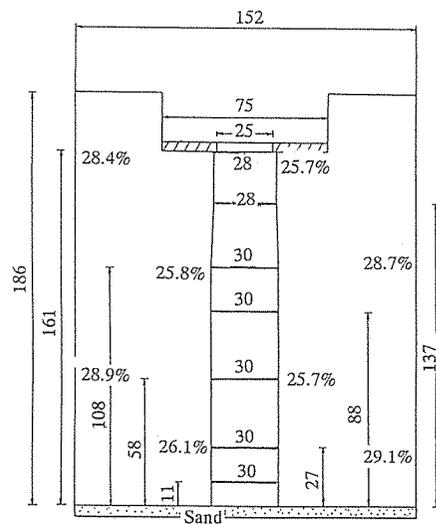

Fig. 9   Deformed Shape of GP–Effect of Stresses on Soil

tive incompressibility. A series of tests were carried out to isolate the contribution of the relatively stiff granular pile on the stress - displacement relations of annular plates. The diameter of the granular pile was kept equal to inner diameter of the annular footing so that only the restraining effect of the granular pile can be measured.

Figure 8 presents a typical stress - settlement responses of the annular plate with inner and outer diameters equal to 25 mm and 50 mm respectively and with GP of 25 mm dia. The stress - settlement response of the footings with the granular pile is stiffer than those without the pile even though the granular pile per se does not carry any load directly. The degrees of improvement defined as the ratio of stresses with and without granular pile at displacements of 5 and 10 mm for the three footings (outer diameters of 50, 75 and 100 mm) are respectively 1.64 and 2.0, 1.3 and 1.38 and 1.14 and 1.25. The restraining effect increases with increasing applied stress or displacement The granular piles not only provide restraining effect but also permit drainage of excess pore pressures, thus allowing the footings to carry larger loads. The increased stiffness of the soil arises from possibly three mechanisms, viz., the lateral restraint (prevention of inward soil displacements), drainage and mobilised interfacial shear resistance by which part of the stresses carried by the soil are transferred to the granular pile. This restraining effect is more if the outer diameter of the annular footing is smaller. Such a result may appear contrary to what is anticipated but on closer examination, the results are consistent. Larger the outer diameter of the footing, lesser is the contribution of the granular pile to the restraining effect.

The measured water contents of the soil and the shape of the GP (Fig. 9) corroborate the postulated mechanisms. The water contents of the soil close to the granular piles at all depths are one to two percentage points less than those farther away. The deformed shape of the GP at the end of the test, indicates that the diameter of the GP is reduced near the its top due to the lateral stresses from the soil. The actual installed diameter of the granular pile is as mentioned earlier, some what larger, about 28 to 30 mm. For a loading plate of 75 mm outer diameter, slight reduction in GP diameter is discernible in the top 50 mm depth of the stone column as in an extension test.

6. Conclusions

The paper presents an experimental study of the interactions between the size and shape of the applied load, the thickness of the granular pad laid on top of the ground, the granular pile and the soft soil. Model tests were carried out in tanks into which reconstituted soft soil beds were prepared. On each reconstituted bed, four load tests, one each on untreated ground, on a single granular pile, on a granular piled raft and on a group of three pile groups, were conducted. Based on the tests in the different series of tests, the following conclusions are arrived at: 1. Granular piles can be

effectively used even for small isolated footings and as part of piled rafts; 2. The granular pad laid on top distributes the applied loads over larger areas which in turn tend to confine the granular pile over greater depths and induces a stiffer response from them; 3. The design of the granular pad should be incorporated in the design of granular pile reinforced soil; the thickness of the pad can be one to two times the diameter of the granular pile; 4. Granular piles facilitate dissipation of excess pore pressures generated in the soil surrounding them and thus permit larger effective stresses and settlements to be mobilised; and 5. The stresses transferred to the soil by the loading plate and the granular pad force the zone of bulging of the granular pile further down to depths of the order of two to four diameters, thus increasing the bulging capacity of the granular piles.

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■著者略歴
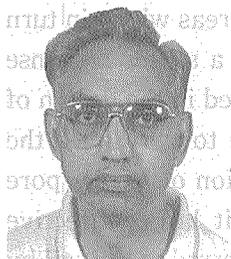
M. R. Madhav
(マダフ)

1960年　アンドラ大学工学部土木工学科
　　　　卒業（工学士）
1961年　インド科学大学修士課程修了
　　　　（工学修士）
1967年　　同上　博士課程修了（ph. D）
1967年　インド工科大学カンプール校・
　　　　講　師
1969年　　同　　上・助教授
1978年　　同　　上・教　授
1992年2月―1993年12月　佐賀大学低平
　　　　地防災研究センター教授
1997年9月―1997年12月　佐賀大学低平
　　　　地防災研究センター
　　　　外国人研究員（客員教授）

三浦　哲彦
(みうら　のりひこ)

1963年　九州大学工学部土木工学科卒業
1984年　佐賀大学理工学部教授
1991年　低平地防災研究センター長（併
　　　　任）
1994年　佐賀大学理工学部長（併任）
1996年　低平地防災研究センター長（併
　　　　任）
　　　　工学博士