Load Test Comparisons for Rammed Aggregate Piers and Pier Groups

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Abstract

Design methods used to estimate the settlement below Geopier Rammed Aggregate Pier - supported footings rely on the performance and interpretation of a modulus test conducted on a single Rammed Aggregate Pier element. The test is used to determine the spring stiffness of a single element. However, actual footings are generally supported by multiple elements and the interaction effects between groups of elements are not simulated in the modulus tests.

This paper presents the results of research performed to investigate the interaction effects between groups of Rammed Aggregate Piers installed at test facilities at the University of Utah and Iowa State University. The full-scale field test programs include load tests for individual elements, footings supported by groups of elements, and footings not supported by reinforcing elements. The results of the research demonstrate the increase in bearing capacity that is afforded by the installations of the piers. The results also indicate that a group interaction factor of 1.0 is appropriate for design. This paper is of particular significance because it is used to verify design procedures for a soil reinforcement method widely used in the United States.

Introduction

Rammed Aggregate Piers (RAPs) are widely used in the United States to reinforce unsuitable foundation soils for the support of shallow spread footings (Figure 1). RAP design methods stem from procedures established by Lawton and Fox (Lawton and Fox 1994; Lawton et al. 1994) whereby the soil strata is analyzed in two layers (upper zone and lower zone) where the upper zone is defined by the length of the installed elements. The compressibility of the upper zone is characterized from a RAP modulus test which establishes an appropriate spring constant for the piers. The method includes the assumption that the spring stiffness of the piers remains constant whether a single pier is loaded by a plate or a group of piers is loaded by a footing (i.e. the method includes a group interaction factor of unity).

Recently, full-scale load tests performed on groups of piers have been conducted by researchers at the University of Utah and at Iowa State University. The data set for the Utah site includes an individual pier modulus test, a load test performed on a five pier group, and a load test performed on a footing not supported by RAPs. The data set for the Iowa site includes two individual pier modulus tests, a load test performed on a four-pier group supported by short piers, and a load test performed on a four-pier group supported by long piers. Comparisons of the modulus test and group load test results indicate that the modulus tests provide accurate predictions of the magnitude of upper zone settlement and of the mode of pier deformation.

Construction

Rammed Aggregate Piers are constructed as shown in Figure 1 with the following steps: 1.) an auger is used to drill .63 to .93 m (24- to 36-in.) diameter holes 1.7 to 9.7 m (5 to 30 ft) into the ground, 2.) a bottom bulb is constructed by placing open-graded highway base course stone in the bottom of the hole and ramming the stone into the bottom soils, 3.) the pier shaft is constructed by ramming thin lifts of well-graded highway base course stone into the cavities using a specially-designed high energy impact rammer and a beveled tamper foot. The shape of the beveled tamper foot is important because it facilitates the increase of lateral stress in the soils surrounding the installed piers (White et al. 2000). This significant increase in lateral stress combined with the high density of the stone created by the installation process provides the unique strength and stiffness inherent in the RAP system (Handy 2001, Wissmann et al. 2001)

Design Methods

Existing design methods stem from those provided by Lawton and Fox (1994). The soil profile is characterized by two distinct soil layers: the upper zone and the lower zone (Figure 2). The settlement within the upper zone is computed by treating the footing as a rigid steel plate, the RAP elements as stiff springs and the matrix soil as soft springs. Because the piers are stiffer than the matrix soil, footing-bottom stresses concentrate to the piers, thereby reducing the applied stress on the matrix soil. The settlement of the upper zone (s_{uz}) is estimated using Equation 1 in which the upper zone is the zone of soil defined by the depth of the piers (Lawton and Fox 1994, Fox and Cowell 1998):

$$s_{uz} = q_g / k_g = q\ [R_s / (R_s\ R_a - R_a + 1)] / k_g \qquad (1)$$

where q_g is the stress applied to the top of the piers, k_g is the stiffness modulus value of the piers, q is the average footing-bottom stress, R_s is the ratio of the stiffness of the piers (k_g) to the stiffness of the matrix soil (k_m), and R_a is the ratio of the cross-sectional area of the piers to the footing-bottom area.

The settlement of the lower zone soils, extending below the bottom of the piers, is estimated using conventional geotechnical analysis approaches, allowing for an increase in stress from the footing and the compressibility of the lower zone soil.

Modulus Tests

This method for computing upper zone settlement depends on the spring stiffness of the piers (k_g) which is typically determined with a single-pier modulus test (Figure 3). The pier spring stiffness is determined from the slope of a plot of top-of-pier stress vs top-of-pier deflection. Because the modulus tests are fitted with telltales, the test results may also be used to evaluate the mechanical behavior of the piers at high loads (Wissmann et al. 2001). As shown in Figure 3, the slope of the top-of-pier stress-deflection plot is steeper at high stress levels than at low stress levels. At high stress levels, for conditions in which the telltale shows no appreciable deflection, the pier response is characterized by radial bulging into the matrix soils surrounding the pier shaft. For conditions in which the telltale deflects downward along with the top of the pier, the high stress levels mobilize tip resistance at the bottom of the piers.

Utah Load Tests

The Utah load tests were performed under the auspices of researchers from the University of Utah at a site along the alignment of the I-15 renewal project in Salt Lake City, Utah (Figures 4 and 5). As shown in Figure 4, site subsurface conditions at the site consisted of soft Lake Bonneville interbedded clay and silt deposits characterized by CPT tip resistances generally on the order of 1 MPa (10 tsf). Three tests were performed at the I-15 site: 1.) a modulus test was performed on a single .6 m (24-inch) diameter pier extending to 2.4 m (8.0 ft) below grade; 2.) a group load test was performed on a 2 m (6.5 ft) wide square concrete footing supported by five Rammed Aggregate Piers extending to 2.4 m (8.0 ft) below grade; 3.) a full scale footing load test was performed on a 2 m (6.5 ft) square footing supported at grade without RAP reinforcement. The load testing apparatus is shown in Figure 5.

A comparison of the load test results for the modulus test pier and the RAP-supported group test is shown in Figure 6. The response of the test piers within the group test is determined by assuming that the measured load is evenly distributed to all piers in the group. The stress applied to each pier is computed as the quotient of the pier load to the cross-sectional area. The results shown in Figure 6 indicate that the response of the individual pier modulus test closely follows the stress-deflection response of the piers in the pier group.

A comparison of the load test results for the two full-scale footing tests are shown in Figure 7, where the applied footing load is plotted against measured footing settlement. At a deflection of 25 mm (1 in.), which is common foundation settlement design criteria, the test results shown in Figure 7 indicate that that the footing supported by unreinforced soil supports a load of about 620 kN (139 kips). At the same settlement criterion, the footing supported by the RAP elements supports a load of 2000 kN (450 kips). Using the 25 mm (1 in.) deflection level as a basis of comparison, the RAP supported footing has more than 3 times the bearing capacity of the unreinforced footing.

Iowa Load Tests

The Iowa load tests were performed under the auspices of researches from Iowa State University at the site of the construction of a box culvert at a bridge in Pottawattamie County, Iowa (Hoevelkamp 2002). As shown in Figure 8, subsurface conditions at the site consist of very soft alluvial silty clay with CPT tip resistances on the order of 0.3 to 0.4 MPA (3 to 4 tsf). Four load tests were performed at the Iowa site: 1.) a modulus test was performed on a single 0.76 m (30-in.) diameter pier extending to 2.3 m (7.5 ft) below grade; 2.) a group load test was performed on a 2.3 m wide (7.5 ft) square concrete footing supported by four Rammed Aggregate Pier elements extending to 2.3 m (7.5 ft) below grade; 3.) a modulus tests was performed on a single 30-in. diameter pier extending to 4.6 m (15 ft) below grade; 4.) a group load test was performed on a 2.3 m wide (7.5 ft) square concrete footing supported by four Rammed Aggregate Pier elements extending to 4.6 m (15 ft) below grade.

A comparison of the load test results for the “short” (2.3 m) long modulus test pier and the RAP-supported group test is shown in Figure 9. The response of the piers in the group test is established by normalizing the measured load by the number of piers in the pier group (4) and by the cross-sectional area of the individual piers. The left panel of Figure 9 shows the top of pier deflections and the right panel of Figure 9 shows the telltale deflections. The test results shown in Figure 9 indicate that the response of the individual pier modulus test closely follows the stress-deflection response of the piers in the pier group for both the top of the pier and for the telltales. Comparisons of the top of pier and telltale responses for both the modulus test and the group piers indicate that bottom of pier tip resistances are mobilized when the applied top of pier stresses exceed about 470 kPA (10 ksf). These data indicate that, for the short tests, the mode of deformation observed in the modulus test pier closely matches that of the group test piers, where the mode of deformation is the mobilization of tip stresses.

A comparison of the load test results for the “long” (4.6 m) long modulus test pier and the RAP-supported group test is shown in Figure 10. The response of the piers is determined by normalizing the measured load by the number of piers in the pier group (4) and by the cross-sectional area of the individual piers. The left panel of Figure 10 shows the top of pier deflections and the right panel of Figure 10 shows the telltale deflections. The test results shown in Figure 10 indicate that the response of the individual pier modulus test closely follows the stress-deflection response of the piers in the pier group for both the top of the pier and for the telltales, which exhibited only minor deflections. Comparisons of the top of pier and telltale responses for both the modulus test and the group piers indicate that the onset of pier bulging occurs when the applied top of pier stresses exceed about 520 kPA (11 ksf). These data indicate that, for the long pier tests, the mode of deformation observed in the modulus test pier closely matches that of the group test piers, where the mode of deformation is bulging.

Conclusions

This paper presents the results of individual pier modulus tests and full-scale footing load tests for footings supported by Rammed Aggregate Piers. Data is presented for tests conducted by researchers at sites in Utah and Iowa. The test data indicate:

1. For both sites and for footings supported by either short piers or long piers, the results of individual pier modulus tests closely match the response of groups of piers when the data is plotted as top-of-pier stress vs. deflection.
2. The observations presented above suggest that the modulus test data provide good predictions of the spring stiffness of the piers in the "upper zone", where the upper zone is defined as the depth of soil reinforced by the piers.
3. Observations of telltale response for tests conducted on short piers indicate that pier tip stresses are mobilized at high top of pier pressures. This mode of deformation is observed in both the modulus test piers and in the response of piers within pier groups.
4. Observations of telltale response for tests conducted on long piers indicate that pier bulging controls deformations at high top of pier pressures. This mode of behavior is observed in both the modulus test piers and in the response of piers within pier groups.
5. Comparisons of load tests conducted on a footing supported by five RAP elements with a footing supported by unreinforced soil shows that the RAP supported footing exhibits three times the bearing capacity of the "bare" footing at the 25 mm (1-in.) deformation criterion.

Acknowledgments

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Figure 1: RAP Construction

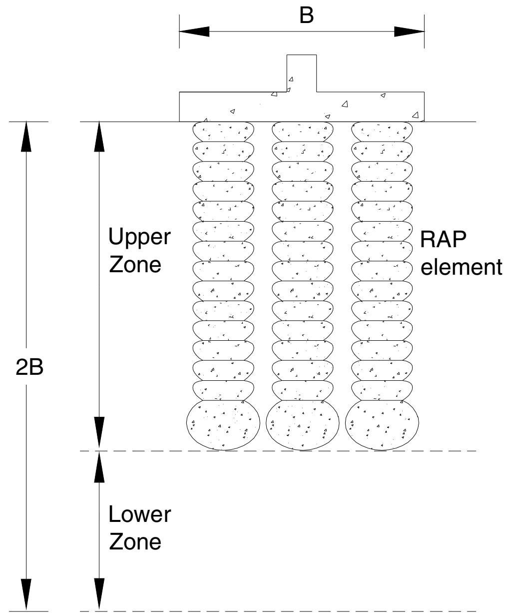


Figure 2: Schematic showing design approach

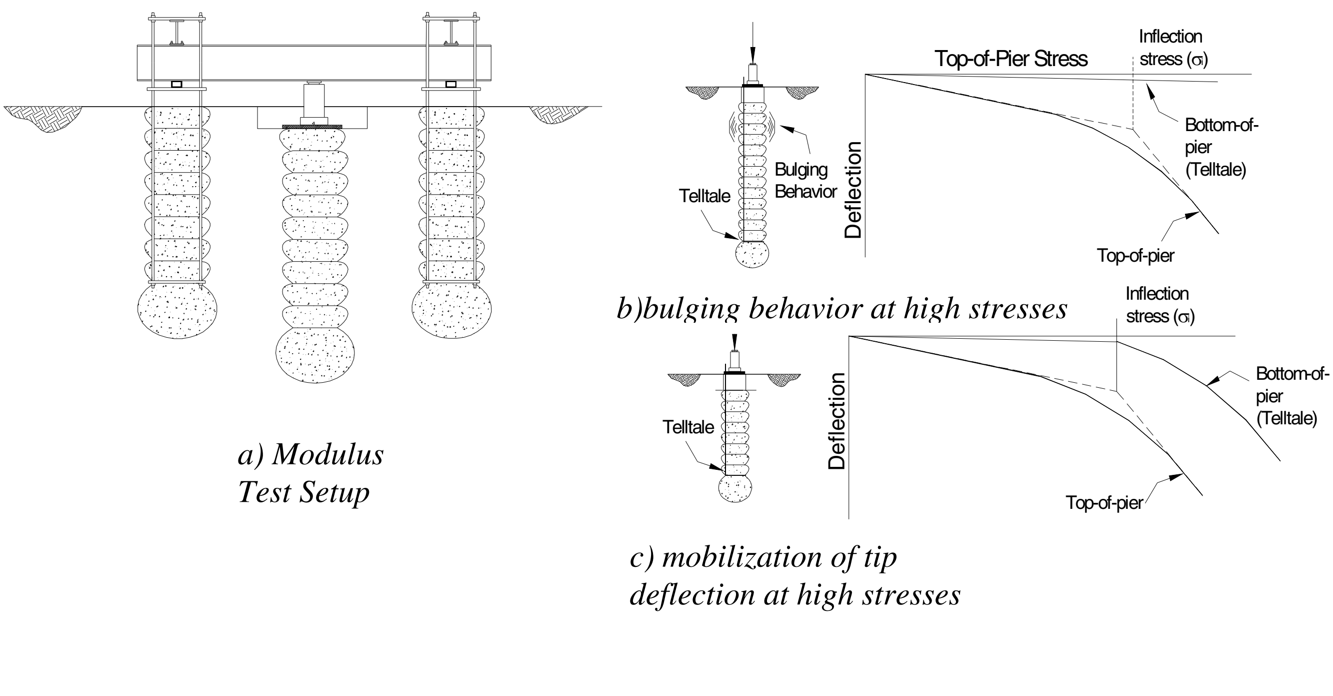
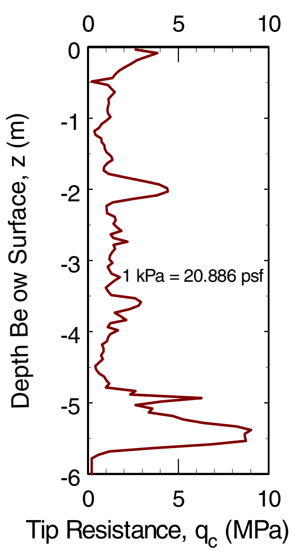
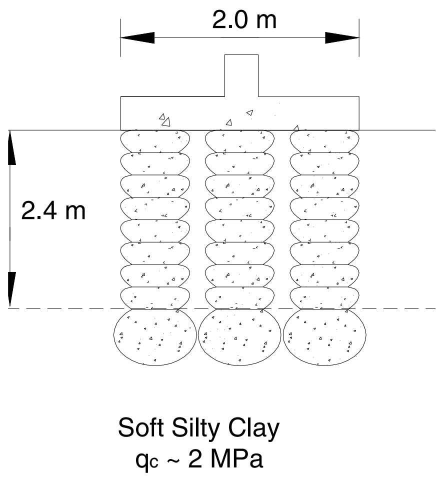


Figure 3: Modulus test results and interpretation

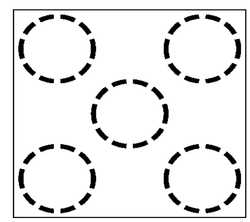
a)Site Layout



b)Subsurface Profile



c)Test Setup



d) Plan View of Footing

Figure 4: Subsurface profile at Utah site

Figure 5: Utah load testing apparatus

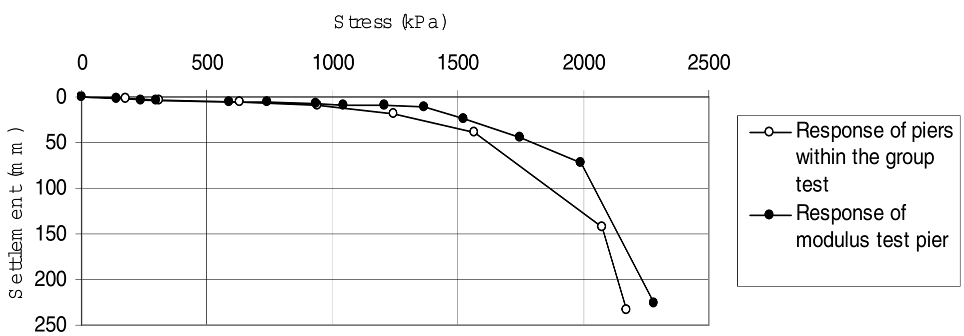


Figure 6: Utah modulus test vs group test comparison

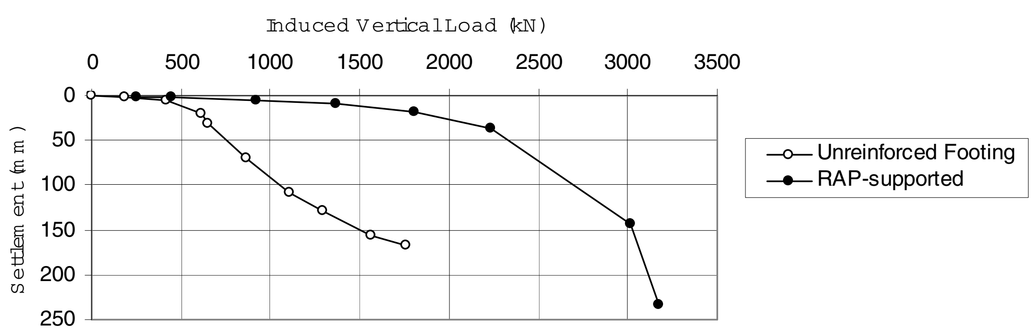


Figure 7: Utah group load test comparisons

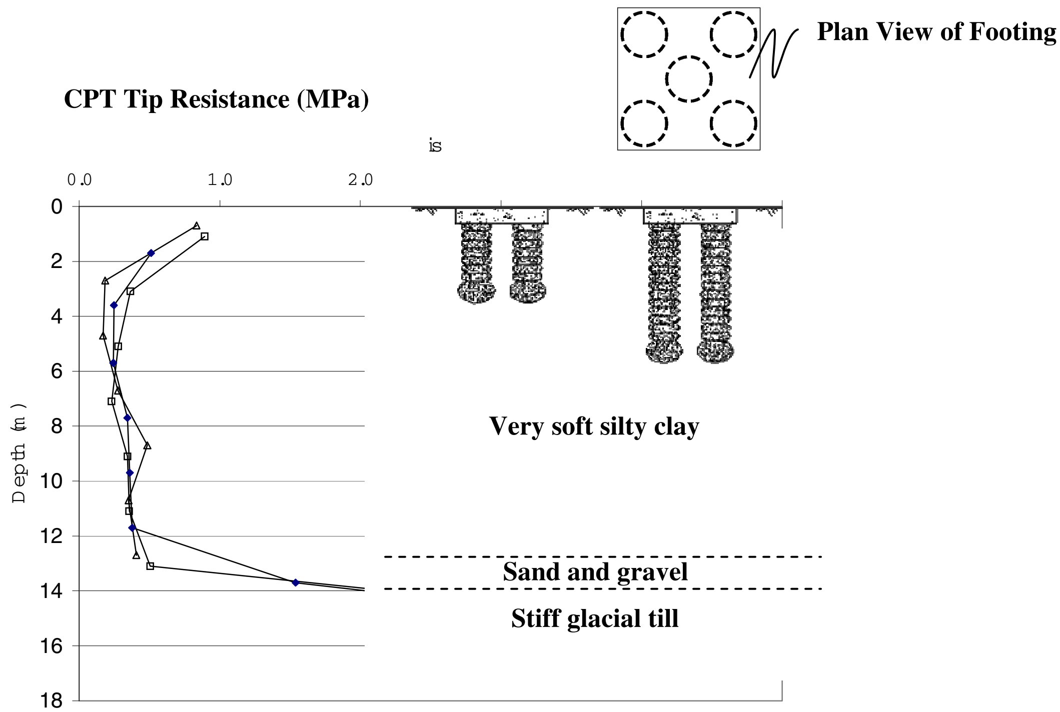
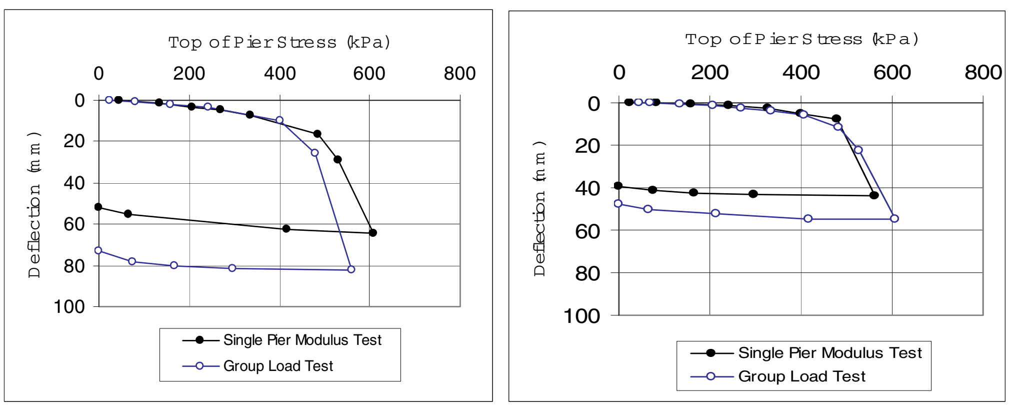
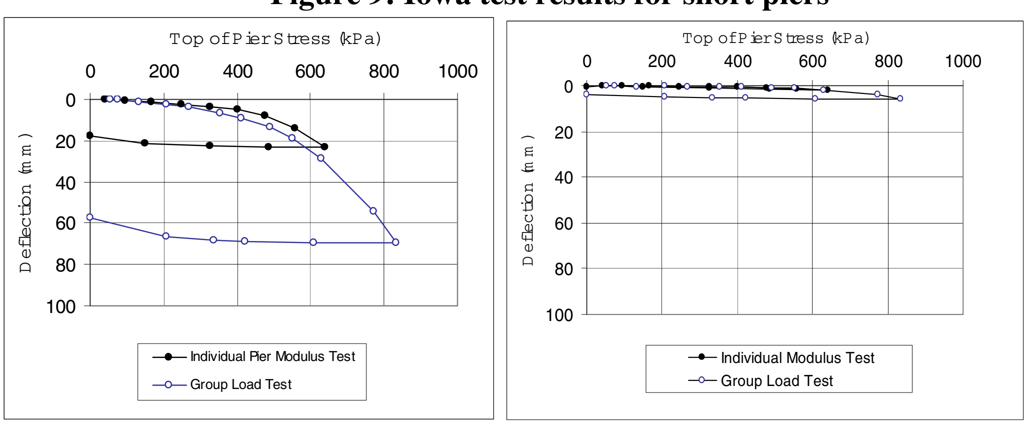


Figure 8: Iowa site subsurface conditions



a) Top of Pier Response *b)Telltale Response*

Figure 9: Iowa test results for short piers



a)Top of Pier Response *b)Telltale Response*

Figure 10: Iowa test results for long piers