GEOTECHNICAL SPECIAL PUBLICATION NO. 126

GEOTECHNICAL ENGINEERING FOR TRANSPORTATION PROJECTS

VOLUME TWO

PROCEEDINGS OF GEO-TRANS 2004

July 27–31, 2004
Los Angeles, California

SPONSORED BY
The Geo-Institute of the American Society of Civil Engineers

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Published by the American Society of Civil Engineers

STABILIZATION OF RETAINING WALLS AND EMBANKMENTS USING *RAMMED AGGREGATE PIERS*™

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ABSTRACT: Highway construction often requires the placement of embankments and earth retaining walls to facilitate grade separations. Instability and settlement occur when these structures are placed on top of weak and compressible soils. Historically, the severity of these problems has been reduced using toe berms and surcharging. More recently, *Rammed Aggregate Piers*™ have been used to avoid the need for extending large right-of-ways required for toe berm construction or for time-consuming surcharging. The installation of Rammed Aggregate Piers reinforces weak and compressible foundation soils prior to construction of earth embankments and walls. The installation of Rammed Aggregate Piers increases the factor of safety against slope instability as a result of the high angle of internal friction (48 to 52 degrees) achieved during ramming and reduces the magnitude and time of settlement by increasing the overall stiffness of the foundation soils and providing a drainage pathway for dissipation of excess pore water pressure.

This paper presents analytical methods used to design Rammed Aggregate Piers to reinforce weak soils and control settlements below highway and railroad retaining walls and embankments. The analytical methods are illustrated by a case history for a Mechanically Stabilized Earth (MSE) wall support project near Houston, Texas. This work is of particular significance because it presents design methodologies and a case history for an effective ground reinforcement technique increasingly used to support highway embankments and walls.

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INTRODUCTION

Geopier® *Rammed Aggregate Piers*™ have traditionally been used to support commercial and industrial building foundations and steel storage tanks. The effectiveness of the Rammed Aggregate Piers is attributed to the lateral prestressing that occurs in the matrix soils during pier construction and to the high strength and stiffness of the piers. In the past few years, there has been a development towards using the elements below highway retaining walls and embankments to reinforce soft soils, improve bearing capacity, control settlements, and accelerate settlements.

The design of the soil reinforcement system uses classical geotechnical engineering approaches in conjunction with field and laboratory tests performed to evaluate the shear strength and compressibility of the elements. This paper presents:

1. The design methods implemented to evaluate the effectiveness of soil stabilization using Rammed Aggregate Piers, and
2. Case history where *Geopier* Rammed Aggregate Piers were used to support the Sienna Parkway MSE walls in Missouri City, Texas as shown in Figure 1.

FIG. 1: Photo of Sienna Parkway MSE Wall

This paper is of particular significance because it provides descriptions of design methods for improving global stability and controlling settlement of embankments using this rapidly growing, patented soil reinforcement method.

GEOPIER® CONSTRUCTION

The construction of *Geopier* Rammed Aggregate Piers is well-described in the literature and shown in Figure 2 (Lawton and Fox 1994, Lawton et al. 1994, Lawton and Merry 2000, Wissmann et al. 2000). The piers are installed by drilling 610 mm (24 inch) to 915 mm (36 inch) diameter holes to depths ranging between 2 m and 8 m (7 feet and 26 feet) below working grade elevations (Figure 2, Panel 1), placing controlled lifts of stone within the cavities, and compacting the aggregate using a specially designed high-energy beveled impact tamper. The first lift consists of clean stone and is rammed into the soil to form a bottom bulb below the excavated shaft (Figure 2, Panel 2). The bottom bulb effectively extends the design length of the aggregate pier element by approximately one pier diameter. The piers are completed by placing consecutive 0.3 m (one-foot) thick lifts of aggregate over the bottom bulb and densifying the aggregate with the beveled tamper (Figure 2, Panel 3). During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity. This action increases the lateral stress in the matrix soil thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface.

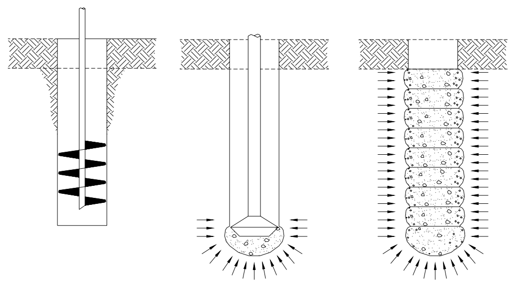

FIG 2: Rammed aggregate pier construction process

The elements may be installed to penetrate through weak and compressible soils thus offering improvements in the composite shear strength and the composite compression characteristics of the reinforced deposit. When installed using open-graded stone, the Rammed Aggregate Piers act as drainage elements affording reduced drainage path lengths and accelerate settlement durations.

FIELD AND LABORATORY TESTS

Field and laboratory tests have been performed to investigate the engineering properties of *Geopier* Rammed Aggregate Piers. The high shear strength afforded by the elements has been measured by means of full-scale direct shear tests performed at the tops of installed elements and triaxial shear tests performed on reconstituted samples. Test results indicate a friction angle of about 49 degrees for piers constructed from open-graded stone (no fines) and a friction angle of about 52 degrees for piers constructed from well-graded stone (5 to 10 % fines) (Fox and Cowell 1998, White et al 2002).

CASE HISTORY: SIENNA PARKWAY MSE WALL SUPPORT

Construction of the Sienna Parkway in Missouri City, Texas required new MSE walls to provide grade changes over existing railroad lines. Maximum retaining wall heights of 9.5 m (31 ft) tall resulted in an estimated average base pressure of 182 kPa (3.8 ksf) and a maximum bearing pressure of 273 kPa (5.7 ksf) according to the Texas Department of Transportation bearing capacity design approach (Texas DOT 2000). The subsurface conditions at the project site consisted of soft to very stiff clay extending to depths on the order of 12 m (40 ft) underlain by medium dense sandy silt and silty sand. In some locations, a layer of sandy silt was encountered at depths of 3 m to 5 m (10 ft to 16 ft). The groundwater table was located at a depth of 4.6 m (15 ft) below the grade. Water content values in the upper portion of the clay profile ranged from 15 to 35 percent. Undrained shear strengths based on pocket penetrometer tests performed in the field and unconfined compression tests performed in the lab ranged from 24 kPa to 215 kPa (0.50 ksf to 4.5 ksf). Geotechnical design parameter values for the clay layer are presented in Table 1.

TABLE 1: Sienna Parkway MSE wall soil parameter values

Soil Parameter	Field / Laboratory Value
Total unit weight, γ_t	19.6 kN/m^3 (125 pcf)
Buoyant unit weight, γ_b	9.9 kN/m^3 (63 pcf)
Average undrained shear strength, S_u	72 kPa (1,500 psf)
Drained friction angle, ϕ	18
Drained cohesion, c	9.6 kPa (200 psf)
Estimated radial coefficient of consolidation, c_r	0.01 cm^2/s (0.9 ft^2/day)

Global Stability

Global stability calculations were performed for the placement of the MSE walls on the unreinforced foundation soils using the conventional limit-equilibrium computer program GSLOPE (Mitre Software Corporation 1999). The analyses indicated that for wall heights greater than 8.2 m (27 feet), the long-term (drained) factor of safety was less than the design criterion of 1.3. Figure 3 shows the results of the stability output for the unreinforced conditions. Overexcavation and replacement, vibro-replacement stone columns, and Geopier Rammed Aggregate Piers were each considered as viable solutions to increase the shear resistance of the foundation soils and improve global stability. Rammed Aggregate Piers were selected based on cost and speed of installation.

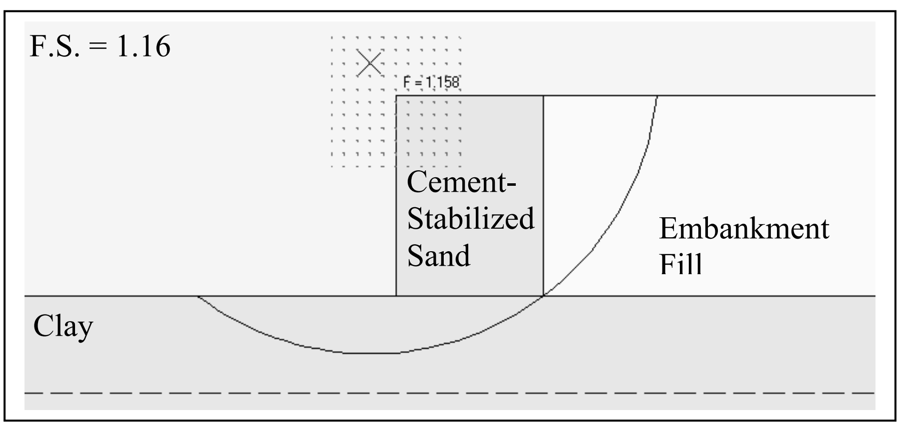

FIG 3: Stability output for MSE wall on unreinforced foundation

Rammed Aggregate Piers installed in weak foundation soils under retaining walls and embankments to intersect critical shearing surfaces and increase the factor of safety against global instability are designed by developing composite shear strength parameter values used to model the zone reinforced with Rammed Aggregate Piers (Figure 4).

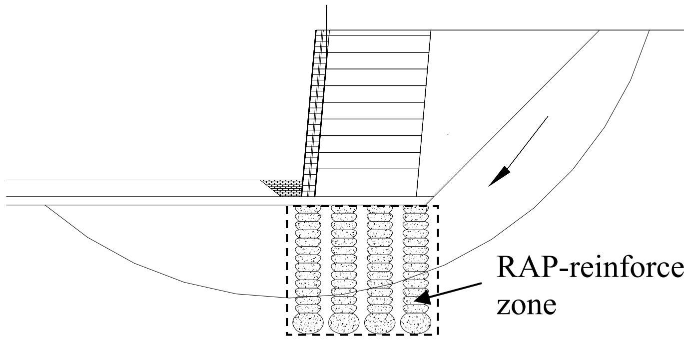

FIG 4: Rammed aggregate pier support of MSE wall

The composite shearing strength parameter values of Rammed Aggregate Pier reinforced soils are computed using the conventional method of calculating the weighted average of the shear strength components of the aggregate piers and matrix soil materials (FHWA 1999). The composite cohesion intercept (c_{comp}) is computed with the expression:

$$c_{comp} = c_g R_a + c_m (1 - R_a) \qquad (1)$$

where c_g is the cohesion intercept of the aggregate, c_m is the cohesion intercept of the matrix soils, and R_a is the ratio of the sum of the element cross-sectional areas to the gross footprint area of the reinforced soil zone. Because the cohesion intercept of the aggregate is zero, Equation 1 reduces to:

$$c_{comp} = c_m (1 - R_a) \qquad (2)$$

The composite friction angle (ϕ_{comp}) is computed with the expression:

$$\phi_{comp} = \tan^{-1}\left[R_a \tan\phi_g + (1 - R_a)\tan\phi_m\right] \qquad (3)$$

where ϕ_g is the friction angle of the aggregate and ϕ_m is the friction angle of the matrix soils. The composite cohesion and friction angle values (Equations 2 and 3) are used to represent the composite shear strength of the soil layers reinforced by the Rammed Aggregate Piers.

In situations where Rammed Aggregate Piers supporting MSE walls or embankments extend through weak soils to a firm bearing layer, the significant difference between the matrix soil stiffness and the Rammed Aggregate Pier stiffness results in a concentration of stress to the tips of the piers. This stress concentration results in a further increase in the composite shear strength (Mitchell 1981). For these cases, composite shear strength parameter values for the Rammed Aggregate

Pier zone are also computed by utilizing a weighted average approach but also incorporate terms to account for the stress concentration (Wissmann et al 2002, FitzPatrick and Wissmann 2002).

Using the estimated design shear strength parameter values provided in Table 2 for embankment soils, subsurface soils, and Rammed Aggregate Piers, stability analyses incorporating *Geopier* soil reinforcement were performed. A composite friction angle (ϕ_{comp}) of 23.7 degrees and a composite cohesion intercept (c_{comp}) of 8.6 kPa (180 psf) were calculated for the Rammed Aggregate Pier reinforced zone using Equations 2 and 3 with an area replacement ratio (R_a) of approximately 10 percent. The results of the drained stability analysis (Figure 5) indicated that the Rammed Aggregate Pier design increased the safety factor to values greater than the design criterion of 1.3. The Rammed Aggregate Pier design incorporated zones of piers installed at spacings of approximately 2.1 m (7 feet) on-center extending up to 5.2 m (17 feet) from the wall face beneath the wall. The aggregate piers were installed to depths of 4.9 m (16 feet) in order to intersect the critical shearing surface. Figure 6 shows the layout of the Rammed Aggregate Pier reinforcement.

TABLE 2: Stability parameter values for design

Soil Layer	Drained Parameter Values	
	ϕ (degrees)	c (kPa)
Embankment soil	18	8.6
Clay	20	9.6
Sandy silt / silty sand	30	0
Rammed Aggregate Pier	48	0

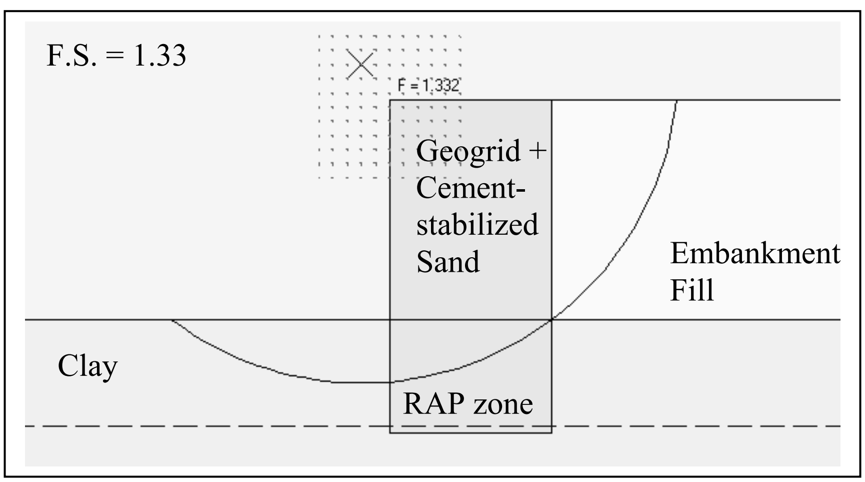

FIG 5: Stability output for Rammed Aggregate Pier-reinforced soil

Bearing Capacity

The placement of 31-foot tall MSE walls induced significant bearing pressures on the foundation soil. Calculations for the bearing capacity of the unreinforced soils indicated that the maximum applied bearing pressure exceeded the allowable bearing capacity of the unreinforced soils, requiring ground improvement.

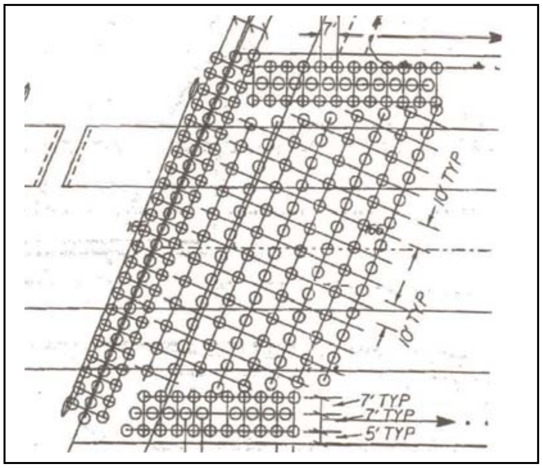

FIG 6: Rammed Aggregate Pier layout

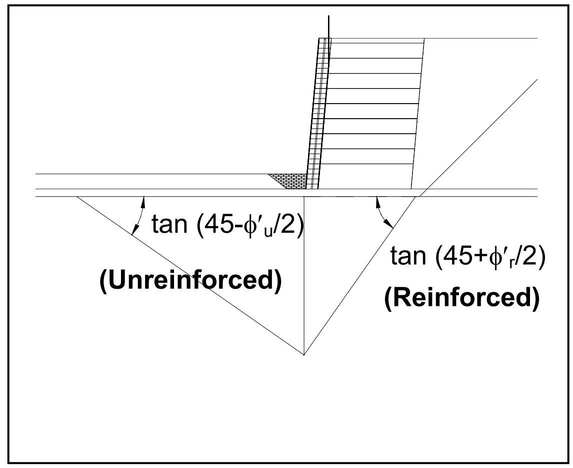

FIG 7: Rankine's lower-bound bearing capacity solution

Rammed Aggregate Piers were used to increase the allowable bearing pressure at the toe of the wall and increase the factor of safety against bearing capacity failure. The allowable bearing pressure incorporating the Rammed Aggregate Piers was evaluated using a procedure developed from Rankine Lower-Bound planar approaches and modified by a factor to account for limit-equilibrium behavior. The suggested procedure is presented in Barksdale and Bachus (1983), with a slight modification suggested by Hall et al. (2002), and includes the following steps:

a. Determine composite strength parameter values based on a weighted average of the matrix soil and Rammed Aggregate Pier shear strengths and the stress concentration factor for the vertically-stratified zone beneath the wall.

b. Calculate the Rankine lower bound solution for bearing capacity by equilibrating the average stresses acting within two blocks of slipping soil as shown in Figure 7.

c. Apply a conversion factor to the Rankine lower bound solution to arrive at an upper bound solution. The conversion is based on comparisons between Rankine lower bound solutions and Terzaghi upper bound solutions for a number of similar cases.

d. Calculate factor of safety by dividing the Terzaghi upper bound solution by the bearing pressure exerted by the wall.

Using the design approaches described above, calculations indicated Rammed Aggregate Piers installed at an area ratio of 10 percent, as required for global stability, increased the allowable bearing pressure to 555 kPa (11.6 ksf), a value that was sufficient to provide the required factor of safety of 2.0.

Settlement Control

The Rammed Aggregate Pier settlement control design methodology is based on a two-layer settlement approach is described by Lawton et al. (1994), Lawton and Fox (1994), Fox and Cowell (1998), and Wissmann et al. (2002). The installation of Rammed Aggregate Pier elements within the aggregate pier-reinforced zone, referred to as the upper zone, creates a stiffened reinforced zone with reduced compressibility that controls settlement of transportation structures. The settlement below the aggregate pier-reinforced zone, referred to as the lower-zone, is evaluated using conventional geotechnical analysis approaches. The total settlement of the transportation structures is evaluated as the sum of the upper zone settlement and the lower zone settlement.

Settlement in the Rammed Aggregate Pier-reinforced zone is related to the average applied bearing pressure, the cross-sectional area coverage ratio, the stress concentration ratio between the Rammed Aggregate Pier elements and the matrix soil, and the stiffness of the Rammed Aggregate Pier (Wissmann et al 2002, FitzPatrick and Wissmann 2003).

To control settlements beneath the center portion of the MSE wall, Rammed Aggregate Piers were installed 3.0 m (10 feet) on center, extending to depths of 4.9 m (16 ft). The 0.91 m (36 inches) constructed element diameter resulted in an area replacement ratio of 0.07. A conservative estimated Rammed Aggregate Pier stiffness modulus value for the elements was 27.2 MN/m^3 (100 pci). Using this value, estimates of settlement within the reinforced soil zone were approximately 2.5 cm (1 inch), only 10 percent of the predicted settlement with no reinforcement.

Modulus tests are performed on Rammed Aggregate Piers to evaluate the stress-deflection behavior of the Rammed Aggregate Pier and the pier stiffness. The setup and results of the modulus test performed at the site are shown in Figure 8. The modulus test results indicated that the actual Rammed Aggregate Pier stiffness was approximately 105 MN/m^3 (385 pci) at the top-of-pier design stress of 710 kPa. This value was more than three times the assumed design stiffness and confirmed the parameter values assumed in the settlement control design.

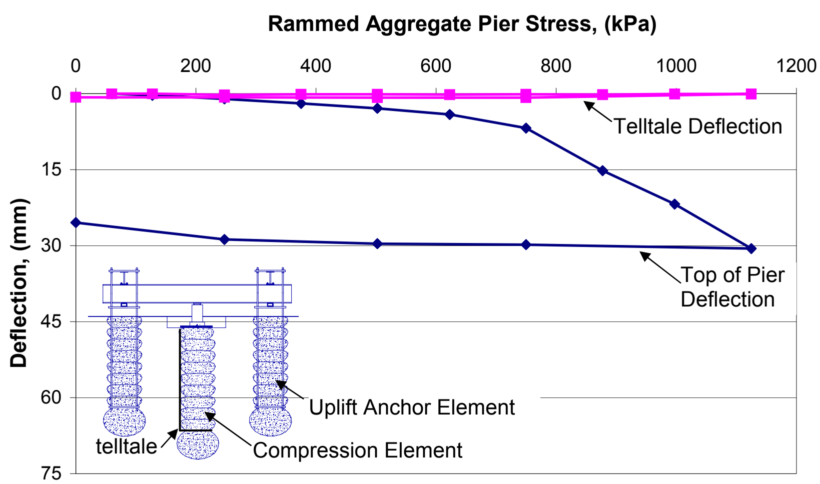

FIG 8: Rammed Aggregate Pier Modulus test results

Settlement Rate

Aggregate Piers reduce the time of consolidation settlement by two primary mechanisms (Han and Ye 2001):

- When open-graded stone is used for pier construction, the piers act as a vertical drain and reduce the drainage path length within the matrix soils for the dissipation of excess pore water pressure.
- The stress concentration that occurs to the tops of the stiff Rammed Aggregate Piers reduces the vertical stress on the consolidating matrix soils.

The design approach estimates the rate of consolidation by horizontal drainage based on a modified time factor for radial flow that incorporates the stress concentration ratio and spacing of the aggregate piers (Han and Ye 2001).

Using the Han and Ye approach, nearly 90 percent of the consolidation settlement within the reinforced zone was estimated to occur within a two week time period. Conventional vertical consolidation calculations (without reinforcement) indicated a duration of more than 3 months may be required to achieve similar levels of excess pore water pressure dissipation. As a result of the installation of the Rammed Aggregate Piers, the rate of consolidation was significantly increased, limiting the post-construction settlement of the walls.

CONCLUSIONS

This paper summarizes the design approaches associated with *Geopier* Rammed Aggregate Piers for improving global stability, improving bearing capacity, controlling settlement, and increasing the rate of settlement below MSE walls and embankments. The high shear strength exhibited by the aggregate elements allows for substantial increases in the composite shearing resistance beneath walls and embankments, thereby providing higher global stability factors of safety. The high element stiffness significantly increases the composite stiffness of the reinforced zone, thus reducing total settlement magnitudes. The settlement rate is increased as a result of both radial drainage provided by the elements and reduction of applied surcharge pressure on the matrix soil from stress concentration to the pier elements. A case history is presented where Rammed Aggregate Piers were used to provide economical solutions to improve global stability and bearing capacity, increase settlement rates, and reduce settlement magnitudes.

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