TECHNICAL BULLETIN NO. 8

SUPPORT OF STORAGE TANKS USING RAMMED AGGREGATE PIERS®

This Technical Bulletin discusses the design of Rammed Aggregate Piers for supporting large-diameter above-ground storage tanks. Aboveground storage tanks apply high bearing pressures on foundation soils. This may result in excessive total and differential settlement and edge stability performance issues, impacting the serviceability of the tank and result in the need for costly repairs, releveling, or tank closure or replacement. The installation of Rammed Aggregate Piers increases the composite strength and stiffness of compressible foundation soils. The piers exhibit a high angle of internal friction that increases the shearing resistance to control edge stability around the perimeter of the tank.

1. BACKGROUND: DESIGN ISSUES FOR TANKS

The construction of large diameter above ground storage tanks (ASTs) results in applied bearing pressures that typically range from 2,000 psf to 6,000 psf depending on the tank height and specific gravity of the contained product. In weak soils or poor quality fill, the high bearing pressures may exceed the bearing capacity shear strength of the soil around the perimeter of the tank resulting in edge instability. Edge instability leads to excessive settlement at the tank perimeter, "mushrooming" of the foundation soils and tank distortion.

The tank bearing pressures also may result in sizeable total and differential settlements, depending on soil compressibility. Large total settlements often may be tolerated provided that accommodations are made for flexible piping connections and joints. Differential settlements remain a concern, however, because they may lead to tank distortion. The combination of edge instability and excessive settlement may significantly impact the performance of storage tanks.

Solutions to prevent excessive settlement and edge instability problems beneath large flexible-bottom tanks include the use of deep foundations with structural mat foundations, overexcavation and replacement of compressible soils, staged tank loading with provisions for releveling, and Rammed Aggregate Piers. Factors such as schedule, performance, and cost play large roles in the determination of the most effective solution for support of the tanks. The costs associated with deep foundations and structural mat foundations are often prohibitive for large diameter tanks. Overexcavation and recompaction is usually avoided because of difficulties with groundwater and the potential for shoring. The length of time typically required for staged loading may not be available and brings risks associated with tank releveling. The superior stiffness coupled with support capacity to provide reliable, settlement control often makes the Rammed Aggregate Pier solution a cost-effective solution that delivers superior performance compared with other solutions.

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2. RAMMED AGGREGATE PIER CONSTRUCTION

Geopier Rammed Aggregate Piers (RAPs) are constructed by drilling out a volume of compressible soil to create a cavity and then ramming select aggregate indo the cavity in thin lifts using a patented beveled tamper. Impact® Rammed Aggregate Piers are installed in soils subject to caving in an alternative fashion using a hollow mandrel to drive to the design depth. Aggregate placed down the center of the hollow mandrel fills the cavity and is compacted in thin lifts as the mandrel is raised and lowered to achieve compaction. The ramming action during construction of the Rammed Aggregate Piers causes the aggregate to compact vertically and to push laterally against the matrix soil, thereby increasing the horizontal stress in the matrix soil. Rammed Aggregate Pier construction results in a very dense aggregate pier with superior strength and stiffness, exhibiting high angles of internal friction on the order of 48 to 52 degrees (White 2004). The high friction angle is attributed to dilation of the aggregate when subject to shearing stresses. The construction processes allows for a high level of confidence in the superior stiffness and significant shearing resistance afforded by the Rammed Aggregate Piers.

3. TANK PERFORMANCE IMPROVEMENTS USING RAMMED AGGREGATE PIERS

As show in figures 1 and 2, Rammed Aggregate Piers are used to:

1. Increase the shear resistance beneath the perimeter of the tank to improve the edge stability factor of safety.
2. Reinforce and stiffen the compressible soils beneath the footprint of the tank to control both total and differential settlement.

The selected reinforcement approach depends on the foundation soil conditions, applied tank pressures, design criteria, and project budget.

Figure 1.
Rammed Aggregate Pier
Reinforcement For Edge Stabilization

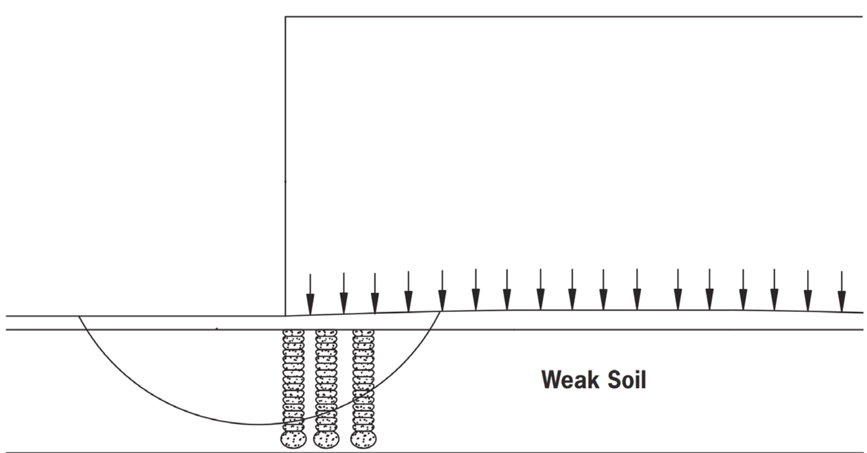
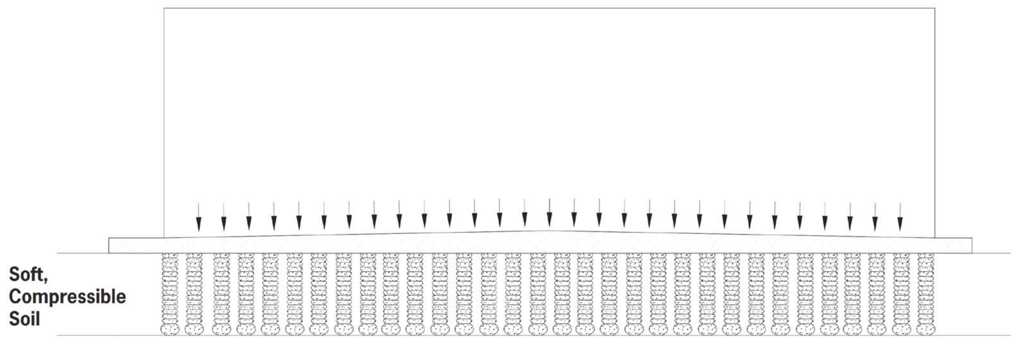


Figure 2.
Rammed Aggregate Pier
Reinforcement For Settlement Control



3.1 SHEAR REINFORCEMENT DESIGN FOR EDGE STABILIZATION

The design of shear reinforcement to improve the edge stability factors of safety is determined from the results of two-dimensional limit equilibrium analyses performed to evaluate the factor of safety against instability. The factor of safety against instability is the ratio of the resisting moment to the destabilizing moment (Duncan 1987). Many computer programs, such as PCSTABL, UTEXAS, SLOPE/W, SLIDE, and GLSOPE, are currently available for performing these conventional analyses. The input parameters required to perform the analysis include tank height and pressure, soil stratigraphy, soil unit weight, soil shear strength (cohesion and friction angle), and the phreatic surface elevation.

Stability analyses are performed by incorporating a Rammed Aggregate Pier-reinforced zone within the model where the parameter values within the zone represent the composite RAP/matrix soil shear strength. The composite shearing strength of Rammed Aggregate Pier-reinforced soils is computed using the conventional method of calculating the weighted average of the shear strength components of the Rammed Aggregate Piers and matrix soil materials (FHWA 1999). The composite shear strength (t_{comp}) is expressed in the following equation:

$$t_{comp} = \sigma'_v \tan \phi'_{comp} + c'_{comp}, \qquad \text{Eq. 1.}$$

where σ'_v is the effective vertical stress for the layer, ϕ'_{comp} is the composite angle of internal friction, and c'_{comp} is the composite cohesion intercept.

The composite cohesion intercept (c'_{comp}) is computed with the expression:

$$c'_{comp} = c'_g R_a + c'_m (1-R_a), \qquad \text{Eq. 2.}$$

Where c'_g is the cohesion intercept of the Rammed Aggregate Pier aggregate, c'_m is the cohesion intercept of the matrix soils, and R_a is the ratio of the Rammed Aggregate Pier area to the gross footprint area of the reinforced soil zone.

Because the cohesion intercept of the Rammed Aggregate Pier aggregate is taken to be zero, Equation 2 reduces to:

$$c'_{comp} = c'_m\,(1\text{-}R_a)\,. \qquad \text{Eq. 3.}$$

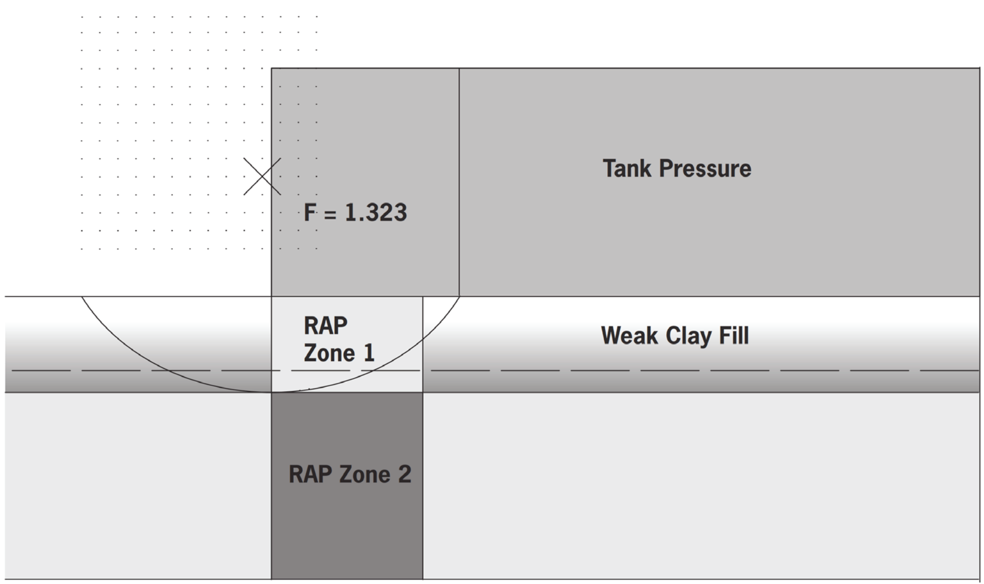
The composite friction angle (ϕ'_{comp}) is computed with the expression:

$$\phi'_{comp} = \arctan\,[R_a \tan\,\phi'_g + (1\text{-}R_a)\,\tan\,\phi'_m], \qquad \text{Eq. 4.}$$

Where ϕ'_g is the friction angle of the Rammed Aggregate Pier aggregate and ϕ'_m is the friction angle of the matrix soils.

The Rammed Aggregate Pier-reinforced zone is designed to increase the shear resistance of the weak soil beneath a new tank or adjacent to an existing tank where potential shear surfaces may develop. Within the reinforced zone, the composite cohesion and friction angle values (Equations 2 through 4) represent the composite shear strength of the soil zones reinforced by the aggregate elements. A sample output of an edge stability analysis is shown in Figure 3. Analyses are performed on a trial and error basis by varying the area coverage (R_a) within the Rammed Aggregate Pier zone until the design factor of safety is obtained. More detailed information on modeling the Rammed Aggregate Pier-reinforced zone can be found in Geopier Foundation Company's Technical Bulletin No. 5 (FitzPatrick and Wissmann 2002).

Figure 3.
Sample Edge Stability
Computer Output



3.2 SETTLEMENT CONTROL OF TANKS

The Rammed Aggregate Pier settlement control design methodology is based on a two-layer settlement approach as described by Lawton et al. (1994), Lawton and Fox (1994), Fox and Cowell (1998), and Wissmann et al. (2002). The installation of Rammed Aggregate Piers within the Rammed Aggregate Pier-reinforced zone, referred to as the upper zone, creates a stiffened, engineered zone with reduced compressibility that reduces the settlement of tanks. The settlement below the Rammed Aggregate Pier-reinforced zone, referred to as the lower-zone, is evaluated using conventional geotechnical analysis approaches. The total settlement (s_{tot}) is evaluated as the sum of the upper zone settlement (s_{uz}) and the lower zone settlement (s_{lz}):

$$s_{tot} = s_{uz} + s_{lz} \quad . \qquad \text{Eq. 5.}$$

3.2.1 SETTLEMENT IN THE RAMMED AGGREGATE PIER - REINFORCED ZONE

The settlement of the Rammed Aggregate Pier-reinforced zone (upper zone) is estimated with Hooke's law:

$$s_{uz} = \frac{qI_{\sigma}H_{uz}}{E_{comp}} \quad . \qquad \text{Eq. 6.}$$

Where q is the tank bearing pressure, I_{σ} is the average stress influence factor in the upper zone (typically assumbed to be 1.0), H_{uz} is the thickness of the reinforced upper zone layer, and Ecomp is the composite elastic modulus of the reinforced upper zone layer. Values for E_{comp} are computed as the weighted average of the elastic modulus of the Geopier RAP elements (E_g) and the upper zone matrix soil elastic modulus (E_m):

$$E_{comp} = E_g\,R_a + E_m\,(1\text{-}R_a) \; , \qquad \text{Eq. 7.}$$

where R_a is the area replacement ratio.

Selected values for E_g depend on both the intrinsic elastic modulus of the constructed pier and on the ability of the foundation to apply concentrated stress to the tops of the piers. For rigid concrete foundations, full values of E_g may be used because the stress concentration ratio is equivalent to the pier/soil stiffness ratio. Smaller values of E_g are selected for soil embankments and flexible walls that cannot apply concentrated stresses as efficiently and thus cannot make full use of the pier stiffness values.

The upper zone settlement methodology provides for a determination of the deflection of the rammed aggregate pier, but not of the matrix soil between the piers. Because of the sizeable stiffness contrast and the use of a granular pad overlying the piers, the majority of the applied stresses are attracted to the engineered material. This stress concentration provides the benefit of having uniform settlement within the RAP-reinforced zone.

3.2.2 SETTLEMENT BELOW THE RAMMED AGGREGATE PIER-REINFORCED ZONE

The settlement below the Rammed Aggregate Pier-reinforced zone (s_{lz}) is evaluated using conventional geotechnical approaches, consisting of either elastic settlement analyses or consolidation analyses using the familiar expressions:

$$s_{lz} = \frac{qI_{\sigma}H}{E_m} \; , \qquad \text{Eq. 8.}$$

and

$$s_{lz} = c_c \left[\frac{1}{1+e_o}\right] H \log \left[\frac{P_0 + qI_{\sigma}}{P_0}\right] \qquad \text{Eq. 9.}$$

where q is the average bearing pressure applied by the tank, H is the thickness of the lower zone, E_m is the matrix soil elastic modulus within the lower zone, and c_c is the matrix soil coefficient of compressibility, e_o is the initial matrix soil void ratio, and P_0 is the initial vertical effective stress at the mid-point of the compressible layer. The average change in pressure with depth is the product of the applied pressure (q) and the stress influence factor, I_{σ}. The stress influence factor within the lower zone is estimated using elastic stress distributions that depend on the depth to the middle of the layer and on the tank diameter. For large diameter tanks, the influence factor may be considerably larger than customary for conventional foundation settlement analyses.

Typically, the elastic modulus settlement approach (Equation 8) is used to estimate settlement in granular soils and heavily over-consolidated cohesive soils. Matrix soil equivalent elastic modulus values may be estimated using published empirical correlations from SPT N-values, undrained shear strengths, CPT tip resistances, or other insitu tests. The consolidation settlement approach (Equation 9) is often used to evaluate settlement in normally-consolidated or lightly-overconsolidated cohesive soils.

4. DESIGN CONSIDERATIONS FOR TANKS SUPPORTED BY RAMMED AGGREGATE PIER ELEMENTS

While the design approach for the support of large diameter storage tanks is similar in concept to the support of conventional shallow foundations, there are details of the design and additional considerations that are noteworthy. These details include total and differential settlement criteria and granular pad design, foundation support and tank retrofits as discussed below.

4.1 SETTLEMENT CRITERIA

The Rammed Aggregate Pier system makes it possible to tailor the design (pier spacing and length) to accommodate different levels of settlement control. By defining the settlement criteria, a design is prepared that is the most cost-effective solution while meeting settlement expectations. For example, for tanks with greater settlement tolerances, a design consisting of wider spacing and fewer reinforcing elements would be utilized to provide more economical support for the structure.

4.2 DIFFERENTIAL VERSUS TOTAL SETTLEMENT

Many settlement criteria will include limits for both total and differential settlement. The differential settlement is often established based on the differential settlement between the perimeter of the tank and the center of the tank. Additionally, some tank owners require a particular differential settlement criterion around the perimeter of the tank.

While Rammed Aggregate Piers are used to control total settlement, another major benefit of the system is the reduction of differential settlement between both the center and tank edge as well as around the tank perimeter. The differential settlement control results from the creation of the uniform engineered zone with significantly reduced compressibility and increased stiffness. Tanks placed on the Rammed Aggregate Pier-reinforced zone settle more uniformly and experience reduced levels of differential settlement. Because of the superior level of differential settlement control, it is often feasible to support tanks that undergo large total settlements provided piping fixtures are attached with flexible connections.

4.3 GRANULAR PAD DESIGN

For most tank support applications, a granular pad is provided over the tops of the Rammed Aggregate Pier-reinforced zone. The granular pad provides a mechanism to transfer the applied pressures from the tank bottom to the stiff reinforcing elements as a result of arching action that occurs within the pad as shown in Figure 4.

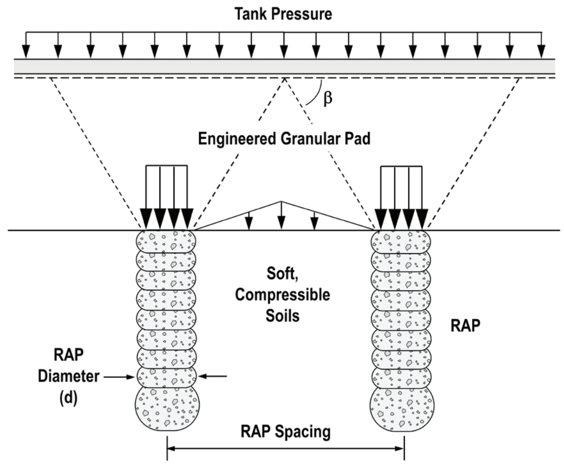


Figure 4.
Granular Pad Design
To Develop Arching

A specific granular pad thickness is required to transfer the majority of the applied tank stresses to the piers. The minimum pad thickness (t) is estimated by the following equation:

$$\frac{\tan ß(s - d)}{2} \qquad \text{Eq. 10.}$$

Where s is the RAP center-to-center spacing, d is the RAP diameter and ß is the angle of arching in the granular pad which is approximately 60 degrees. In some cases, the use of structural geogrid layers, such as those offered by Tensar Corporation, may be used to develop more efficient load transfer to the piers, thereby reducing the thickness of the granular pad and reducing ß from 60 degrees to 45 degrees. The gradation of the granular pad must consist of well-graded structural fill material which meets the project geotechnical recommendations. Compaction of the granular pad must be performed to levels achieving 95% of the maximum dry density according to ASTM D-1557 unless otherwise specified.

4.4 RINGWALL AND ROOF FOUNDATION SUPPORT

When not designed as a floating roof tank, many tanks transfer roof loads to isolated foundations within the tank footprint that bear at the base of the tank. In addition, although not always required, some tank designs incorporate a ringwall foundation to support the steel tank shell. Rammed Aggregate Piers are installed beneath both the roof support footing and the ringwall foundation to reinforce the soils and control settlement of these structural elements. The number of piers required for isolated column support depends on the roof load, while the spacing of the piers beneath the ringwall depends on the loads applied to the ringwall as well as the edge stability requirements.

4.5 EXISTING TANK RETROFITS

For existing tanks experiencing edge instability problems that have not yet developed performance problems requiring tank replacement, Rammed Aggregate Piers are installed around the perimeter of the tank to reinforce the weak soils and increase the shear resistance. While the piers do not provide settlement control benefits in these cases, the increased shear resistance provides corresponding increases in the edge stability factors of safety and often inhibits continued tank deformation related to edge instability. While the same design approach is used as described above, higher area ratios are often required to control edge stability with piers installed around the perimeter because of the low normal stress on the reinforced zone compared to the high pressures applied to the piers when installed beneath the actual tank pad. Additionally, because of the required larger number of piers and closer pier spacing, it may not be possible to increase the factors of safety to levels typically used for design of new tanks. For retrofit designs, factors of safety of 1.1 to 1.2 are often used.

5. CONCLUSION

Rammed Aggregate Pier reinforcing elements effectively increase the factor of safety against edge instability and reduce the potential for differential and total settlements of above ground storage tanks. When Rammed Aggregate Piers are installed within the zone of critical shearing surfaces, the high angle of internal friction exhibited by the piers provides significant increases in the shear resistance. Rammed Aggregate Piers are used to reinforce and stiffen compressible foundation soils prior to the placement of new tanks. The Rammed Aggregate Pier-reinforced zone provides significant reduction of both differential and total settlement and is designed to meet the project settlement criteria.

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SYMBOLS USED

ß	=	Angle of arching within granular pad
c_c	=	Coefficient of compression of matrix soil
c'_{comp}	=	Composite cohesion intercept of the RAP reinforced zone
c'_g	=	Cohesion intercept of RAP aggregate
c'_m	=	Cohesion intercept of matrix soil
d	=	RAP diameter
e_o	=	Void ratio of matrix soil
E_{comp}	=	Composite elastic modulus of the RAP-reinforced zone
E_g	=	Elastic modulus of RAP element
E_m	=	Elastic modulus of matrix soil
ϕ'_{comp}	=	Composite angle of internal friction of the RAP-reinforced zone
ϕ'_g	=	Angle of internal friction of RAP
ϕ'_m	=	Angle of internal friction of matrix soil
H	=	Thickness of the compressible layer
H_{UZ}	=	Thickness of the RAP-reinforced upper zone layer
I_σ	=	Stress influence factor
P_o	=	Initial effective vertical stress
q	=	Applied bearing pressure
q_g	=	Top-of-RAP stress
R_a	=	Ratio of sum of the cross-sectional area of RAPs to the gross reinforcement area
R_s	=	Stress concentration ratio between RAPs and matrix soil
S	=	RAP spacing
S_{lz}	=	Settlement below the RAP-reinforced zone
S_{uz}	=	Settlement within the RAP-reinforced zone
S_{tot}	=	Total settlement
σ'_v	=	Effective vertical stress
t	=	Granular pad thickness
t_{comp}	=	Composite shear strength

NOTES

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