Numerical Modeling of Rammed Aggregate Pier Construction

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ABSTRACT

The Rammed Aggregate Pier® foundation system serves as an alternative to deep foundations and overexcavation/replacement of compressible soils. Several case histories have documented the use of rammed aggregate piers for support of tanks, shallow foundations, retaining walls, and embankments. To investigate the mechanical behavior of the rammed aggregate pier system, numerical analyses of rammed aggregate pier foundations have recently been performed by several researchers. Even though the pier construction process is widely credited for the performance of rammed aggregate piers, these recent investigations have ignored or inadequately considered pier installation in the numerical modeling. This paper investigates how methods of modeling rammed aggregate pier construction influence predictions of the load-displacement response and material stress state of model piers. The modeling methods described in this paper involve: (1) prescribed cavity wall displacement, and (2) prescribed cavity volumetric strain. These methods are incorporated into finite element analyses of modulus load tests conducted on isolated piers. Effects of pier construction modeling method and magnitude of prescribed cavity expansion are investigated by comparing predicted pier load-displacement relationships and stress-dependent stiffness with the results from the field load tests. Stress paths of pier aggregate elements from numerical analyses incorporating the pier construction methods are also evaluated.

INTRODUCTION

The Rammed Aggregate Pier® system is a ground reinforcement technology that serves as an alternative to deep foundations and overexcavation/replacement of compressible soils. Several case histories have documented the use of rammed aggregate piers for support of structures and transportation facilities. Recently, numerical methods have been used to model rammed aggregate pier systems for investigating the mechanical behavior of isolated and grouped piers (Pham et al. 2004, Pham and White 2007, and Chen et al. 2009).

The construction process of rammed aggregate piers begins with drilling a hole approximately 0.76 m in diameter to a pre-defined depth. Loose aggregate is placed in the cavity, which is then compacted using a beveled tamper. This process is repeated to give successive lifts of aggregate, each about 0.3 m thick. The product of the pier construction process is a column of densely-compacted aggregate surrounded by weaker matrix soil.

Aggregate ramming occurring during pier construction forces the aggregate laterally into the surrounding soil, which increases the in-situ horizontal stress in the matrix soil. This cavity expansion may also increase the soil shear strength and stiffness (Suleiman and White 2006). Handy and White (2006a) report that measured lateral stresses after pier installation range up to the Rankine passive pressure computed from soil shear strength parameters.

The rammed aggregate pier construction process is widely credited for the performance of the foundation system, however, many of the recent numerical investigations of rammed aggregate piers have ignored or inadequately considered pier installation in the numerical modeling process. To date, Pham and White (2007) and Chen et al. (2009) have given rammed aggregate pier construction the most consideration in numerical modeling of the intermediate foundation system, using a prescribed lateral displacement to model cavity expansion of two-dimensional axisymmetric and three-dimensional finite element models, respectively. This general approach to modeling rammed aggregate pier construction is evaluated in later sections of this paper.

This paper introduces a new method for modeling the construction process of rammed aggregate piers, namely application of volumetric strain to the pier cavity. Numerical analyses of two separate modulus load tests conducted on isolated piers were performed with PLAXIS 2D finite element code using the proposed volumetric strain method. Numerical analysis results using the proposed modeling method and the displacement cavity expansion method of Pham and White (2007) and Chen et al. (2009) were compared with the measured deformation responses of the two physical rammed aggregate piers, as reported by White et al. (2007). The results of these analyses, which mainly include pier load-displacement relationships and stress-dependent stiffness characteristics, are presented to demonstrate the effect of modeling method on stress conditions and deformation response of model piers. Specific objectives of this paper include: (1) validating the new modeling method using two load tests by comparing numerical predictions with measured pier deformation responses, (2) investigating the effect of modeling method on aggregate stress conditions during pier loading, and (3) documenting the use of pier-soil interface elements for modeling the plunging deformation mode of short rammed aggregate piers.

EXPERIMENTAL RESULTS

Load tests

Two rammed aggregate piers were installed and load tests were performed at a project site in Neola, Iowa. Test parameters are summarized in Table 1. Load test setup, performance, and results have been documented by White et al. (2003) and White et al. (2007).

Selection of these specific load tests for investigating methods of modeling the pier construction process reflects an attempt to incorporate a range of pier lengths and deformation modes into the analysis. The testing program includes one short (P1) and one long (P2) rammed aggregate pier, which exhibited tip deflection and bulging behaviors, respectively. Suleiman and White (2006) present more details about these deformation mechanisms of aggregate piers. Also, the two rammed aggregate piers were installed at the same site, which was investigated in detail using in-situ and laboratory testing methods (see White et al. 2003).

Table 1. Load testing program at Neola, Iowa.

Test Parameter	P1	P2
Pier Length (m)	2.7	5.1
Telltale Depth (m)	2.4	5.1 [1]
Deformation Mode	Tip deflection	Bulging

[1]Telltale installed before construction of bottom bulb (White et al. (2003)

Subsurface conditions

The subsurface profile at the Neola, Iowa site consists of a 1-m-thick layer of desiccated fill overlying 13 m of compressible alluvial clay (CL). These soils are underlain by glacial till and weathered shale bedrock. Groundwater is encountered approximately 2 m below the ground surface. Engineering and index properties of the soil were evaluated using both laboratory and in-situ testing methods. Results of these tests are summarized in White et al. (2003). Natural moisture content of the alluvial clay ranges from 30 to 45 percent. Undrained shear strength based on UU triaxial tests is about 30 kPa. A CD triaxial test on a soil sample from a depth of 4.2 m exhibited an effective friction angle (ϕ') of 24 degrees and effective cohesion (c') of about 12 kPa (White et al. 2003).

NUMERICAL ANALYSIS

Constitutive modeling

Constitutive parameter values were established for the site-specific soil and aggregate materials based on triaxial tests. The hardening soil model is used to describe the constitutive behavior of soil materials. The soft soil model is used to describe the behavior of aggregate, in part, because slight softening behavior was observed during triaxial testing of aggregates. The primary purpose of using the soft soil model was to account for the stress-dependent material response which is not achieved using the Mohr-Coulomb model. The model parameters of soil materials were selected to provide the best fit of both stress-strain and excess pore pressure responses observed during the laboratory testing, whereas selection of the model parameters for the aggregate material focused primarily on aggregate strength and were based loosely on stress-strain behavior. Even though CD triaxial tests were not conducted on aggregate samples obtained during pier construction, constitutive modeling referenced the stress-strain responses of crushed gravel reported by White et al. (2002), which documented the stress-strain response of different aggregate materials used in rammed aggregate pier construction. Selection of the most appropriate triaxial test dataset for modeling rammed aggregate pier material behavior was based on aggregate type (crushed gravel in this case), gradation, and shape characteristics. The crushed gravel CD sample exhibited an effective friction angle of 43 degrees and effective cohesion of 55 kPa (see White et al. 2002).

Drained conditions were assumed for foundation soils, whereas undrained conditions were assumed for aggregate material. The drained soil conditions are partially supported by load testing procedures that promote measurement of a drained response. Pore pressure observations documented by Handy and White (2006b), which describe rapid dissipation of excess pore pressures following pier installation, also support the use of drained material conditions.

Table 2. Constitutive modeling parameter values.

Model Parameter	Desiccated Fill	Alluvial Clay	Aggregate
Soil model[1]	Hardening	Hardening	Soft Soil
γ_t (kN/m^3)	19.0	19.0	21.0
ϕ' (degree)	35	22	40
c' (kPa)	2	1	60
ψ (degree)	0	3	5
υ_{ur}	0.2	0.2	0.2
E_{50}^{ref} (kPa)	9,000	5,000	—
E_{oed}^{ref} (kPa)	4,500	4,000	—
E_{ur}^{ref} (kPa)	27,000	15,000	—
p^{ref} (kPa)	25.5	25.5	—
m	1.0	0.9	—
R_f	0.96	0.9	—
K_0^{nc}	0.426	0.625	0.357
λ^*	—	—	0.007
κ^*	—	—	0.003

[1]PLAXIS models

Finite element model description

The rammed aggregate piers are modeled axisymmetrically with standard fixities using PLAXIS 2D. The overall model dimensions are 8 m wide (i.e., radial distance) by 15 m tall, as shown in Figure 1. These specific dimensions were selected to eliminate model boundary effects. Rammed aggregate piers are modeled with 380-mm radii and lengths corresponding to lengths of physical piers being modeled. The pier cap is modeled as a linear elastic, nonporous material with thickness of 460 mm and radius equal to the pier. An unstructured mesh that consists of 15-node, triangular elements is used. Groundwater is modeled using a phreatic surface. Two methods were used to model the pier construction process, namely prescribed displacement and volumetric strain methods. The details of both of these methods are discussed in the following sections.

Prescribed displacement modeling procedure

The initial stress condition in the procedure used by Pham and White (2007) is established with the aggregate and the cap of the pier in place. Initial stresses are generated using the K_0 procedure, in which the in-situ horizontal effective stresses are calculated using the vertical effective stress and the predefined K_0 value (based on internal friction angle).

The pier installation process is modeled by deactivating the pier aggregate elements (to simulate an empty cavity) and applying outward uniform displacement along the cavity wall and downward displacement at the bottom of the cavity. Pham and White (2007) recommended subjecting the matrix soil to approximately 40 mm and 80 mm of horizontal and vertical cavity expansion displacement, respectively, which was based on field observations of diameter change after installation of about 80 mm. The modeling process continues with the reactivation of pier aggregate in the expanded cavity and a release of the prescribed displacements. The load tests were then simulated by applying incremental loads to the top of the footing. A similar approach was used by Chen et al. (2009) for the three-dimensional FLAC model, except that a velocity command was applied to the nodes on the cavity wall, which resulted in a radius increase of 40 mm and length increase of 80 mm at the bottom of the pier.

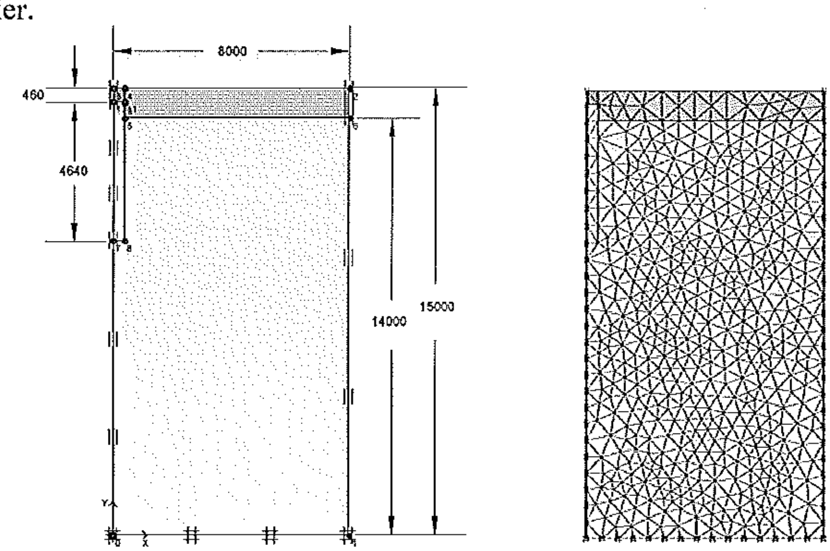

Figure 1. Finite element model of Neola-P2 load test with dimensions in mm.

Volumetric strain modeling procedure

The initial stress condition for the volumetric strain modeling procedure is established using the same approach described above. The proposed method then continues with the following steps:

1. The pier aggregate and cap materials are given properties of the matrix soil in the first user-defined PLAXIS calculation phase. A pre-defined volumetric strain (ranging from 5 to 20 percent for this study) is applied to the soil within the pier cavity limits only using a PLAXIS feature in which the user right-clicks on the material and manually enters the specified volumetric strain.
2. A prescribed vertical displacement of 0 mm is applied to the pier at the ground surface during the volumetric straining stage(s), which ensures that the cavity does not expand above the ground surface, but rather that the expansion occurs radially and vertically downward to compress the matrix soil and change the soil stress condition.
3. After these initial cavity expansion phase(s), the rammed aggregate pier and pier cap properties are returned to those of the aggregate and concrete, respectively, and the prescribed zero-displacement at the ground surface is deactivated.

4. Pier loading includes application of a point load to the top of the pier cap at the axis of symmetry considering that the input value of load is for only one radian (i.e., PLAXIS point load should be multiplied by 2π to give load on physical pier).

This modeling procedure differs from the procedures used by Pham and White (2007) and Chen et al. (2009) in the method of cavity expansion, where the proposed procedure utilizes volumetric strain of cavity material to induce cavity expansion instead of applying a prescribed displacement to the wall of an empty cavity. In addition to offering an easier, more user-friendly method of analysis, the new method results in a more accurate aggregate stress condition and provides improved prediction of the deformation response of isolated aggregate piers.

NUMERICAL MODELING RESULTS

Deformation response of the long rammed aggregate pier

Numerical modeling results are verified by comparing the load-displacement relationships generated by PLAXIS with the results of the full-scale modulus load tests. In addition to load-displacement relationships, stress-dependent stiffness (i.e., stiffness versus pier settlement) are used to assess the prediction capability of the modeling methods. Stiffness is calculated as the ratio of applied vertical stress to measured pier top settlement.

These deformation behaviors for the Neola-P2 load test, which are based on the prescribed displacement cavity expansion modeling method, are shown in Figure 2. The large, black circles represent the measured field data, whereas the small symbols with lines represent the predicted deformation behavior for various magnitudes of cavity expansion.

The prescribed displacement cavity expansion method overpredicts pier settlement under low, working-stress loading conditions for all magnitudes of cavity expansion. The stress-dependent stiffness plots in Figure 2 more clearly support this observation, where the numerical analyses provide predicted stiffness much lower than measured results. The stress-dependent aggregate constitutive model selection and stress conditions in the model aggregate, as described in the next sections, accounts for this behavior. Further, the magnitude of cavity wall displacement necessary for the model to approximate the load-displacement is 100 mm or more. This level of expansion is physically less realistic than the proposed method.

Using the proposed volumetric strain method, the calculated deformation responses of the P2 model pier closely agree with the measured responses [see Figure 3(a)] when the magnitude of induced volumetric strain is 20 percent. With most of the volumetric strain going into radial expansion, 20 percent volumetric cavity expansion give a radius increase of about 36 mm – a close approximation of reported field observations. The authors recognize that physical cavity expansion depends on ramming stress and duration, as well as the matrix soil properties; the appropriate magnitude of imposed cavity expansion will vary for different site conditions. Only slight overprediction of settlement (underprediction of stiffness) between 150 and 250-kN loads is observed. The predicted initial stiffness response shows very good agreement with the measured response in comparison with predictions using the prescribed displacement modeling method.

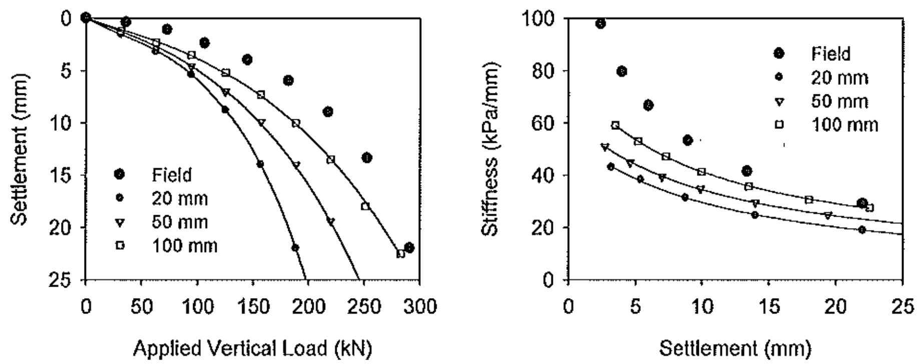

Figure 2. Predicted deformation response of Neola-P2 load test using prescribed displacement cavity expansion modeling method.

Deformation response for short rammed aggregate pier

The short rammed aggregate pier was constructed at the same site using the same installation procedure. The magnitude of cavity expansion used to model the long pier was anticipated to apply to the short pier, as well. However, the numerical model representing the 2.7-m pier (Neola-P1) experienced difficulty in predicting both the pier cap and pier telltale displacement using rigid, fully-bonded interfaces [see Figure 3(b)]. Using the volumetric strain cavity expansion modeling procedure with 20 percent volumetric strain, the deformation response was predicted only up to about pier plunging (i.e., where the slope of the load-settlement curve significantly steepens). Beyond pier plunging, settlement was underestimated and stiffness was overestimated.

Considering how the short pier deformation mode (i.e., plunging) is characterized by mobilization of shear resistance along the entire pier length and high relative displacements between soil and pier elements, the Neola-P1 load test was modeled using elastic-plastic interface elements between the pier and the matrix soil. The predicted pier cap and telltale displacements agreed with the measured pier response when incorporating the strength reduction along the pier-soil interface (R_{inter} equal to 0.55 for soil, fitted to match field data) [see Figure 3(c)], even at post-plunging loads. Interface elements had little effect on the behavior of the long pier, which is attributed to different deformation modes for long and short piers. High relative shear displacements between soil and aggregate elements and associated soil strength reduction are not observed in long piers, where the longer pier lengths provide more resistance to applied loads.

Aggregate stress paths

Pham and White (2007) and Chen et al. (2009) documented stress paths for soil elements adjacent to Neola rammed aggregate piers. Stress states in the soil are associated with a construction-induced increase in horizontal stress and were noted to be on the extension failure envelope, which corresponds to a Rankine passive stress condition. The soil shear stresses which were mobilized through pier loading caused the soil to enter compression space. However, neither Pham and White (2007) nor Chen et al. (2009) documented the aggregate stress paths during construction and loading.

Figure 4 shows stress paths for an *aggregate* element about 0.5 m below the ground surface for the Neola-P2 PLAXIS finite element model. Stress path are provided for both volumetric strain and prescribed displacement cavity expansion modeling methods. These stress paths show the initial stress condition and also the material stress state during pier loading. The prescribed displacement cavity expansion modeling method begins pier loading from an extension (tension) condition (see Point A), which conflicts with the stress condition of physical piers following pier installation. Using the volumetric strain cavity expansion modeling method, however, pier loading begins from a compression condition (see Point B). Further, the mean effective stress at the beginning of loading using the volumetric strain method is significantly higher than for the displacement method. The observed higher-stress condition is justified by Thompson and White (2006), which reports residual vertical stresses in piers after construction exceeding 100 kPa and measured vertical stresses during ramming exceeding 200 kPa. This difference in stress condition of the aggregate at initiation of pier loading, coupled with stress-dependent stiffness behavior of the aggregate (i.e., higher confining stress yields stiffer aggregate response), explains why the proposed modeling method provides better agreement with measured deformation results at lower applied stress levels.

SUMMARY

The numerical investigation presented in this paper documents how methods of modeling rammed aggregate pier construction influence the predictions of material stress state and load-displacement response of model piers. A new, recommended modeling method was evaluated in this paper, namely application of volumetric strain to the pier cavity. The major findings of the numerical study include:

1. Using the proposed volumetric strain cavity expansion method, the calculated deformation responses of model piers closely agree with the measured responses, even under post-failure loading conditions.
2. Interface elements were used to improve modeling of short rammed aggregate piers to simulate the deformation mode experienced in the field (i.e., plunging).
3. The prescribed displacement cavity expansion modeling method results in the pier aggregate being loaded from an extension stress condition, which disagrees with the stress condition anticipated in physical piers following construction.
4. The mean effective stress at initiation of pier loading based on the volumetric strain method is higher than for the prescribed displacement method. This higher stress condition, coupled with stress-dependent aggregate behavior, may explain the improved prediction of pier deformation response at lower stress levels.

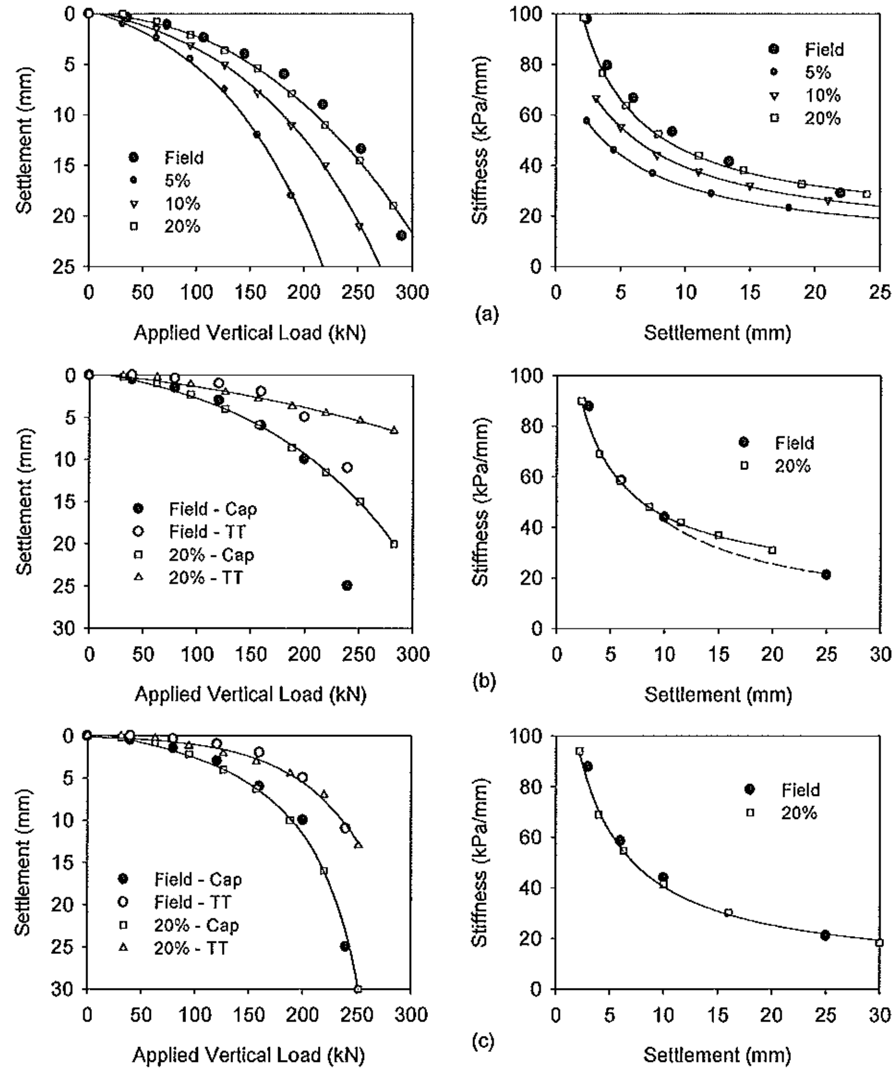

Figure 3. Predicted deformation response of load tests using volumetric strain cavity expansion modeling method: (a) Neola-P2, (b) Neola-P1 without interface element, and (c) Neola-P1 with interface element.

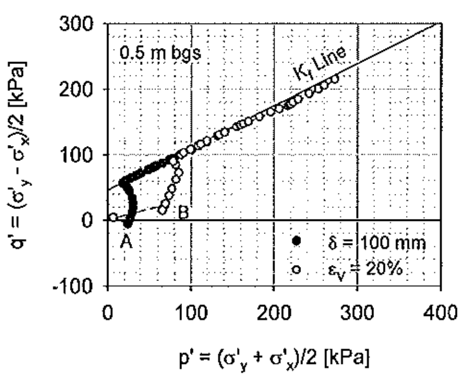

Figure 4. Stress paths for aggregate at 0.5-m depth for prescribed displacement and volumetric strain modeling methods, Neola-P2.

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