Rammed Aggregate Pier Design and Construction in California - Performance, Constructability, and Economics

Tom Farrell MS, GE
Aaron Taylor MS, SE
Farrell Design-Build Companies, Inc.
Placerville, California

ABSTRACT

Faced with an increasing number of poor soil sites being considered for new development in California, Geotechnical and Structural Engineers are turning to current ground improvement technologies to reinforce unsuitable soil and fill in place for conventional footing support. Recommending and designing conventional foundations and slabs-on-grade supported by massive excavation replaced with engineered fill, or designing deep foundations with structural floor slabs are costly and time consuming options. Foundation selection is influenced by long-term settlement performance, management of seismic loads, local constructability requirements, and schedule and cost savings. Rammed aggregate pier supported shallow foundations are one system recommended for building support by engineers. Understanding the basic structural design concepts used with this ground improvement technology allows the structural engineer to design conventional shallow foundations bearing on improved ground and to reduce overall project complexity, schedule and cost.

After a decade of successful project delivery, cost savings, and measured performance in California, Geopier rammed aggregate pier construction has become a main-stream application for public and private projects. This paper discusses rammed aggregate pier performance, constructability, and economics in California.

INTRODUCTION

Engineers have several foundation systems to choose from for different site and loading conditions. When it comes to soft and/or weak soil sites in California, engineers are limited to a handful of alternatives. The "tried and true" driven concrete pile and cast-in-drilled-hole concrete pier are becoming more expensive to build and local constructability requirements have forced engineers to consider and design alternative foundation systems. Various ground improvement techniques such as massive excavation replaced with engineered fill, soil cement columns, rammed aggregate piers, vibro-replacement stone columns, and compaction grouting give the engineer the opportunity to tailor a foundation solution for a particular site condition.

Very similar to massive excavation replaced with engineered fill, rammed aggregate pier (RAP) construction is a technology based on the same principles: remove a soft weak soil then improve its stiffness, its strength, and its ability to manage foundation loads. RAP construction can be considered a discrete excavation and replacement with rammed aggregate (engineered fill). Helpful insights of RAP ground improvement can be gained by understanding the design and construction process; presented next is a brief description of the RAP construction technique and conventional footing design.

RAMMED AGGREGATE PIER CONSTRUCTION

To remove soft and weak soil or fill, individual RAP elements are typically drilled 30 inches in diameter and are constructed to depths ranging from 6 to 30 feet using the simple construction process shown in Fig. 1.

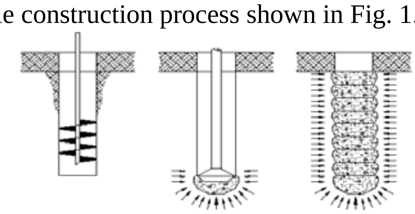

Fig. 1 Rammed Aggregate Pier Construction Process
A. Drill 30" and 33" diameter RAP shafts
B. Ram 2" crushed rock into the "bottom bulb"
C. Ram ¾" to 1½" crushed, road base rock in 12" lifts up to the bottom of footing plus 6" to 12"

The ramming equipment consists of a 45,000 pound hydraulic excavator equipped with a 3,500 pound hydraulic break hammer and a specially designed 45º beveled ram, see Fig. 2. The hydraulic hammer delivers

Fig. 2 Typical RAP Installation Equipment

between 1 to 2 million ft.-lbs. of energy to the ram at approximately 400 blows per minute.

After drilling, the high frequency ramming action of the beveled ram embeds a lift of crushed rock into and compacts the bottom of the drilled shaft, commonly referred to as the "bottom bulb." In weak soil, several cubic feet of crushed rock can be rammed to stabilize the bottom bulb. Once the bottom bulb has stabilized, the rest of the drilled shaft is filled. The equipment rams and embeds thin lifts of crushed rock into the sides of the drilled shaft radially into the adjacent soil. The net effect is an increase in strength and stiffness of the soil mass up to one RAP diameter from the drill edge (Pitt et al 2003).

In comparison to vibro stone columns, RAP elements are rammed into soft and weak soil and not vibrated. Side by side full-scale load tests performed in Iowa show that RAP stiffness is 5 to 10 times greater than vibrated stone columns in the same soil (Pitt et al 2003).

In comparison to soil cement columns or concrete piers, RAP construction compacts and densifies the soil at the bottom of the shaft and radially outward around the shaft. That is, the RAP element is not simply a structural element within the unimproved soil, but also improves the soil. This results in higher end bearing capacity and higher shaft friction around the RAP element.

An analogy can be made with a smooth and deformed reinforcing bar in reinforced concrete. The smooth bar has a good bond and some friction in the concrete, where the deformed bar has a good bond and much higher friction in the concrete. A RAP element is like a deformed reinforcing bar in the improved soil.

CONVENTIONAL FOOTING DESIGN

The design of conventional footings supported on RAP improved soil or fill is no different than footings designed on competent, naturally deposited soil or on engineered fill. The structural engineer needs to understand the RAP improved soil behavior and to design for the appropriate allowable footing bearing pressure.

In practice, each RAP is designed to act as a stiff element in the reinforced soil mass, attracting most of the applied footing load and/or floor slab loads while in most cases permitting the soil between the elements to support a portion of the applied load. The most common conditions that govern RAP footing design include footings bearing directly on RAP elements and footings bearing in engineered fill over RAP elements, see Fig. 3.

Where foundations are in contact with the RAP element, the footing is designed to bear directly on the RAP and the improved soil. Thus, a high bearing capacity of the RAP improved soil (q_c) is used to size the footing, which is typically two to four times the allowable bearing pressure of the unimproved soil (Hall et al 2002). Using ASD load combinations from Chapter 16 of the California Building Code, footings are sized and laid out by the RAP design-builder. Based on this layout, the structural engineer then determines footing thickness and reinforcement using conventional reinforced concrete design. In cases where the footings are not in direct contact with the RAP elements, the footings are sized for the allowable bearing pressure of the engineered fill.

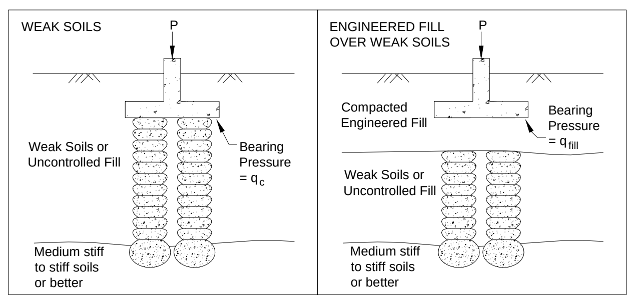

Fig. 3 Conditions Governing Design of RAP Foundations

Design of RAP supported footings falls into two distinct categories:

1) Heavily loaded footings are supported with RAP elements spaced at less than three RAP diameters and are designed as spread footings or small mats between frames and shearwalls. The plan dimensions of footings must be selected to develop full coverage of the RAP elements and to have a RAP area replacement ratio of at least 30%.

2) Continuous footings are supported by RAP elements spaced at greater than three diameters, and may have to structurally span between the RAP elements. As such, for weak soil conditions the continuous footing may be designed as a beam on an elastic foundation, incorporating the corresponding spring stiffness of the RAP elements and the unimproved soil.

The primary properties needed for conventional footing design are RAP stiffness modulus (k_g) and the allowable composite bearing pressure (q_c). These properties are initially derived from the Standard Penetration Test (N_{spt}) and undrained shear strength (s_u) properties of the unimproved soil and are well described in the literature (Lawton 1994, Fox & Cowell 1998, Wissmann 1999, Minks 2001, Majchrzak et al 2004). As discussed later, these values are verified with full-scale modulus load tests at each project site. Preliminary design values for k_g and q_c are shown in Table 1.

Table 1. RAP Stiffness Modulus & Allowable Composite Bearing Capacity for Preliminary Design Estimates

Native Soil properties		k_g & q_c Sands	k_g & q_c Silt and Clay	k_g & q_c Peat
N_{spt}	s_u			
N	(ksf)	(pci) & (ksf)	(pci) & (ksf)	(pci) & (ksf)
3	0.50	165 & 5.0	125 & 4.5	75 & 3.5
6	1.25	225 & 6.0	175 & 5.0	110 & 4.0
9	1.75	260 & 7.0	210 & 6.0	125 & 5.0
12	2.30	285 & 8.0	250 & 7.0	-
16	3.00	310 & 8.5	260 & 7.0	-
25	4.50	325 & 9.0	275 & 7.5	-
>25	5.00	360 & 10.0	300 & 8.0	-

1. For 30-inch RAP elements supporting spread footings with a min. area ratio of 30% (Fox and Cowell 1998).

Ultimate Capacities

Depending on density and strength of the unimproved soil or fill, the ultimate vertical bearing capacity of a RAP element can range from 100 kips up to 300 kips. With the addition of a specially designed structural steel anchor, the RAP can also resist uplift loads generated by earthquakes and wind (Lawton 2000, Caskey 2001, and Wissmann et al 2001). The RAP uplift element can be designed to resist up to 200 kips of ultimate uplift force. In practice, ultimate uplift capacities of 100 to 150 kips are usually specified.

Since the RAP is composed of very dense, crushed rock, it exhibits high sliding resistance to lateral loads. As a result, footings over RAP elements have higher resistance to lateral sliding forces (Lawton 2000 and Wissmann et al 2001). The RAP soil mass exhibits ultimate coefficients of friction between 0.8 and 1.1, which is applied to the entire footing bottom. Appropriate factors of safety are applied to determine allowable design values.

Settlement

Settlement of the RAP supported footing is estimated by modeling it as a rigid plate supported on a system of stiff RAP springs and soft soil springs, and assumes that the

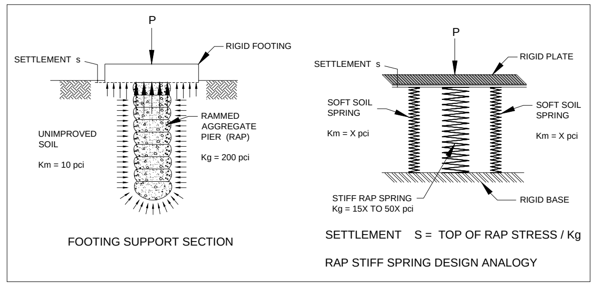

Fig. 4 RAP Stiff Spring Design Analogy

stiff RAP elements and soft soil settle uniformly (Handy 2001), Fig. 4. For equal displacement, the top of the RAP element has concentrated stresses in proportion to the stiffness ratio of RAP to the unimproved soil. In practice, stiffness ratios of RAP to native soil range from 10 to 50.

Total footing settlement is calculated by adding upper zone settlement to lower zone settlement, see Fig. 5. Upper zone settlement is derived by dividing the RAP stress by its stiffness. The lower zone settlement is calculated using classical soil mechanics. A description of the calculations of RAP design can found in Majchrzak et al 2004 and Pitt et al 2003.

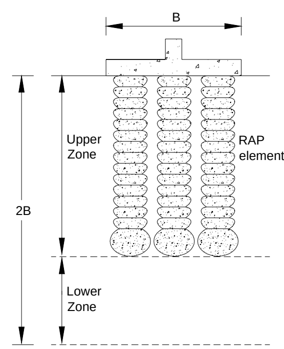

Fig. 5 RAP Upper Zone and Lower Zone Concepts

Floor Slab Support

Floor slab support is also an important and useful application of RAP construction being implemented at soft soil sites in California. A warehouse or distribution center floor slab with area loads of 150 psf or higher, up to 800 psf, can be designed to span 10 to 15 feet over RAP elements in very soft bay mud or weak uncontrolled fill instead of using a more costly pile and grade beam supported structural slab, see Fig. 6. RAP slab support is classified as either slab-on-grade or structural and depends on the fill thickness between the slab and RAP elements. A structural slab design (reinforcing is "active") is required when the slab must span the clear distance between RAP elements. A discussion of this application can be found in Minks et al 2003.

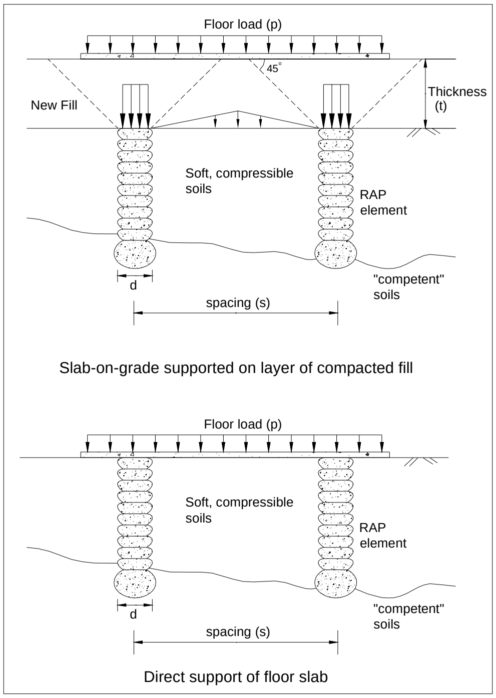

Fig. 6 Conditions Governing RAP Supported Floor Slabs

PERFORMANCE

RAP construction provides the engineer with increased confidence in the performance of the foundation system, both for static loads and dynamic loads. Well defined stiffness of RAP construction and settlement performance are the main reasons for this increased confidence.

Well defined stiffness of RAP construction is proven by:

1. Full scale load tests at every job site.
2. Regularity and simplicity of construction. The RAP rock bucket holds the volume of two 12 inch rammed lifts, ensuring thin rammed lifts for every element installed.
3. A large boring at every RAP element confirms to the Geotechnical Engineer that the site is represented by the soil investigation borings.

Defined Stiffness

During RAP construction in medium to stiff soil layers, the rammer will embed rock into the soil with medium lateral sidewall deflection, and at soft soil layers the rammer will imbed rock with large lateral sidewall deflections, increasing improvement where it is needed. As a result, unidentified soft and weak soil layers are improved with higher rock volumes (rock takes) during construction. This improvement is evidenced by several modulus load test results at soft soil sites in California.

Full scale modulus load tests measure the bearing spring stiffness (stiffness modulus, k_g) of RAP elements. The RAP modulus test is run in general accordance with ASTM D1143 pile load test with modifications specific to RAP construction. Because design parameters are based on full scale load test data, the RAP behavior is well understood, and the data can be used for conventional code design or for performance based design.

Fig. 7 Photo of RAP Modulus Test Set-up

The compression element is loaded to 120% of the maximum RAP top-of-pier stress to measure the stiffness modulus and is then loaded to 200% to measure its pseudo-ultimate capacity (break in the load deflection curve), see test setup in Fig. 7. Although the purpose of the modulus test is to verify the RAP stiffness modulus used for design calculations, the tests also add useful insight into how the RAP behaves in various soils. The failure mechanism of a RAP can be identified during load testing because of telltales installed at the bottom and middle of the element. As shown on Fig.8 at a site in Dublin, the telltale only moved slightly while deformations at the top of the pier increased above the stress of about 25 ksf. This behavior indicates that the RAP is bulging slightly outward at higher stresses instead of plunging (Majchrzak et al 2004). Bulging is the preferred RAP behavior and “limit state.”

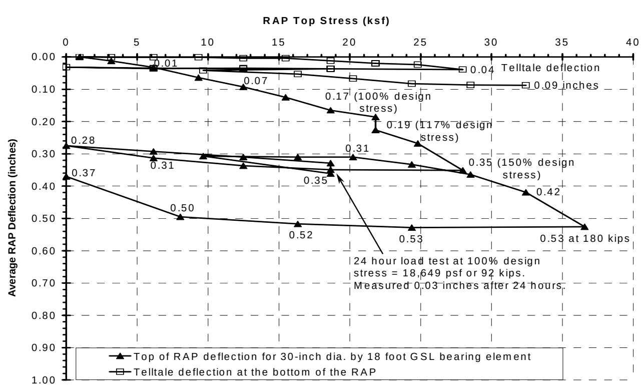

Fig. 8 Modulus Test Results Graph, Dublin

Uplift Performance

A RAP uplift element is constructed almost identical to a bearing only element with the exception that a vertical “dead-man” anchor is placed at the bottom bulb during construction of the element. The structural steel anchor consists of four #7, 75 ksi, Williams Form All Thread Rebar with a minimum ultimate strength of 60 kips each, see structural properties of the rebar in Fig. 9.

Structural Properties	
Minimum Yield	**Ultimate Tensile**
75 KSI (517 Mpa)	100 KSI (698.4 Mpa)
Typical Elongation in 8" bar	
7%-9%	

Unique Thread Form

Fig. 9 All Thread Rebar Properties and Threads

At the bottom, the all thread rebars are bolted to a hot dip galvanized 1-inch thick A36 steel plate. The assembly is protected with a polyurethane spray-on coating at the bolted connection and over the entire plate, see Fig. 10. The top of the all thread rebars receive 4” square bearing plates, which provide the necessary anchorage in the footing. In consideration of long-term reliability, the unique all thread rebars are oversized and hot dip galvanized and then protected by a 25 mil thick high density polyethylene that is tightly bonded to the bar by a flexible bituminous mastic, see Fig. 10. This effectively eliminates migration of moisture and oxygen to the steel, which are requirements for corrosion.

The uplift load test results in Fig. 11 show the repeatability in linear stiffness of a RAP uplift element in soft soil after two multiple cycle events. Based on the

Fig. 10 RAP Uplift Element at UC Davis Math Sciences

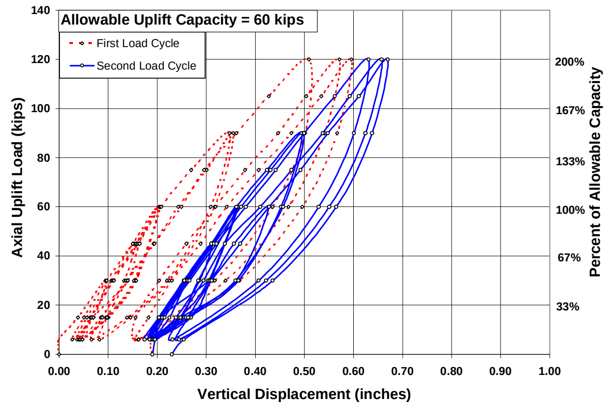

Fig. 11 Cyclic Load Test on 33-inch by 15-foot deep RAP Uplift Element at 1801 L Street in Sacramento.

ASTM D3689 quick pile uplift load test procedure, this test was performed at a project in Sacramento. The soil condition at this site is loose sandy silt and soft silty clay extending 30 feet below the ground surface (bgs) with water at about 18 feet bgs. SPT “N- values” ranged from 2 to 5 blows per foot in the sandy silt and silty clay soil.

For this particular test, the uplift element did not fail. However, in general the behavior of a RAP uplift element is similar to that of a belled concrete pier, in that it begins to progressively heave a large mass of soil at the ground surface as the element reaches its ultimate capacity (Lawton 2000). Note that almost 50% of the initial elastic deflection is in elongation of the steel, well within its prescribed elastic range. The uplift element maintained linear stiffness after multiple overstress cycles.

Settlement Control

With regard to footing design, structural engineers seem to be more familiar with bearing pressures (strength), and less so with the subgrade modulus (stiffness). Sometimes a structural engineer is faced with the choice of either requiring ground improvement below the footings and using moderate bearing pressures for design, or opting instead to use large footings with a low bearing pressure or a deep foundation system with structural slab support. Regardless of the approach, the superstructure must be protected from both total and differential settlement between adjacent columns.

RAP design and construction results in both reduced total settlement and reduced differential settlement (Majchrzak et al 2004). How important is it to control differential settlement? Consider the case of a two-bay concrete moment frame that has differential displacement of ¾” at the middle column. For typical bay lengths and member dimensions, up to 40% of the yield moment can be realized in the beams from this settlement alone.

To provide a long term picture of RAP settlement control, two 6 story structures, one in Sacramento and one in Dublin, were monitored for settlement and are discussed in detail in Majchrzak et al 2004. The following case histories show good uniform settlement control at sites with soft to medium stiff clay soil that extends to depths of 30 feet. At both projects, average 20 to 25 foot deep RAP foundations replaced 75 and 65 foot driven piles

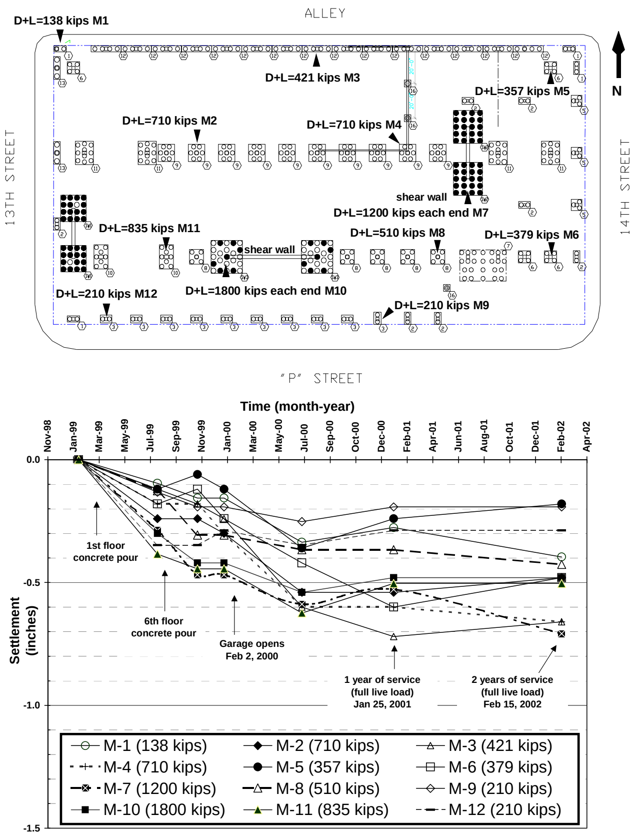

Fig. 12 Surveyed locations & Settlements - Sacramento

In Sacramento, 12 column locations were monitored with gravity dead plus live loads ranging from 138 kips to 835 kips and two shearwalls with dead plus live loads of 1,200 and 1,800 kips at the each end. The results of foundation settlement surveys are plotted against time in Fig. 12. The results indicate that the foundation settlements have ranged between 0.3 and 0.8 inches with both the maximum value and the average of the values less than the design estimates (Majchrzak et al 2004).

In Dublin, several locations where monitored including gravity columns with dead plus live loads ranging from 300 kips to 600 kips and at moment frame mats with dead plus live loads of 1,500 and 2,300 kips. The results of foundation settlement readings for the Dublin site are plotted against time in Fig.13. Actual measured settlements ranged between 0.3 to 0.7 inches with both

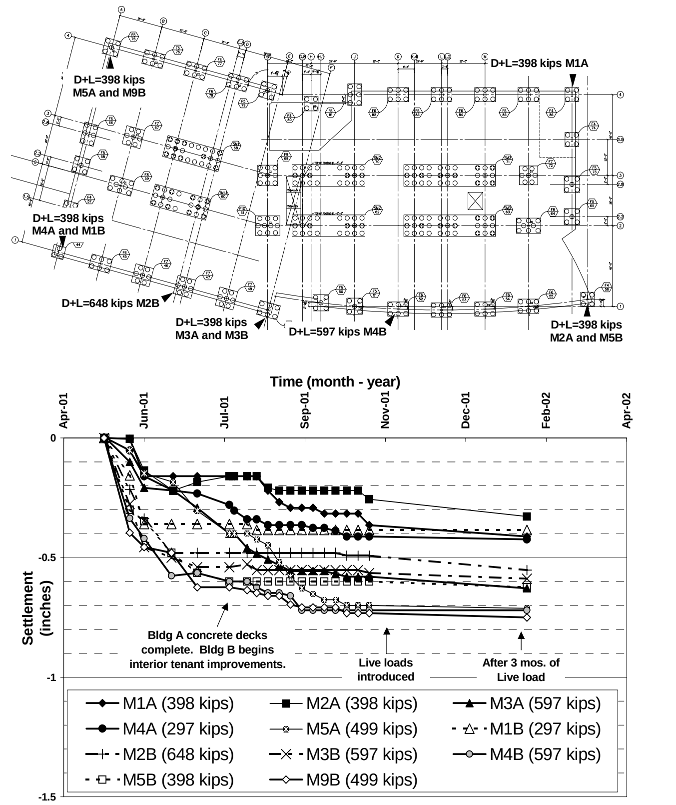

Fig. 13 Surveyed locations & Settlements - Dublin

the maximum value and the average of the values less than the design estimates (Majchrzak et al 2004).

CONSTRUCTABILITY

The repeatable performance exhibited by RAP elements is the direct result of simple construction technologies and quality control. The use of common crushed aggregates available at local rock quarries helps maintain the quality of constructed RAP elements. And the use of specially designed structural steel anchors from Williams Form Engineering ensures the repeatable performance of RAP uplift elements.

From a contractor's perspective, building conventional shallow foundations over improved soil is far easier than constructing pile caps or pier caps and grade beams. In some cases where massive excavation replaced with engineered fill is recommended, but the bottom of the excavation is below or near the water table, using RAP construction can preclude a stringent dewatering system.

Because of the improvement in adjacent unimproved soils and uncontrolled fill, RAP elements do not always need to go to a competent deep soil layer, which reduces construction difficulties. This feature makes the system applicable in most soft and weak soil conditions. Typical production rates for RAP elements approach 40 to 60 elements per day. The speed of the RAP construction, allows contractors to start footing excavation earlier, getting the building superstructure out of the ground faster than a deep foundation project.

From a quality control perspective, RAP construction is observed and tested by the Geotechnical Engineer of Record as with any other foundation system. From modulus load testing to the daily dynamic cone penetrometer tests and bottom stabilization tests, the Geotechnical Engineer's field representative also records drill depths, average ramming times per lift, aggregate types per lift, average lift thickness, and unusual soil conditions encountered in the drilled shafts. RAP quality control is similar to that of concrete pier quality control, except that RAP construction includes a full scale load test on every job. A detailed discussion of quality control testing for rammed aggregate pier installations can be found in the ICBO ES Report ER-5916 (2002).

Due to the relative size of RAP construction equipment, overhead restrictions are seldom an issue. As well, tight city and urban sites in residential areas lend themselves to the technique because RAP construction produces low noise. This is because the hammer is muffled down the shaft 80% of the time. In addition to the low noise effects, the high frequency, transient vibrations are nearly imperceptible at distances of 25 to 30 feet from the rammer. Unlike the steady state vibrations of driving concrete piles at peak particle velocities reaching 2 inches per second, vibrations from RAP construction are under 0.2 inches per second at 10 feet from the rammer. For city zero lot line sites, RAP elements can be constructed as close as 18 inches from an existing building, eliminating the need for shoring.

The main limitation of RAP construction is depth. That is why RAP construction has been coined "the intermediate foundation system." Normally consolidated soft clays or liquefiable soils that extend more than 30 feet below the ground surface cannot be improved due to equipment restrictions. While the deepest RAP elements constructed in California are 36 feet bgs, 90% of RAP elements are less than 20 feet deep. In addition, casings are sometimes temporarily added for caving soil conditions.

Green Construction

RAP elements can be enhanced by the addition of or substitution with recycled concrete and recycled aggregate. In 2003, DPR Construction Inc. completed construction of their regional office in Sacramento and received the silver medal award for Green and Sustainable construction from the US Green Building Council in the LEED™ certification program (USGBC 2004). The use of local construction materials in the RAP foundation assisted DPR in receiving this award by adding LEED™ points. This was the first privately owned project in the Central Valley to receive the honor. At a recent project in Modesto, Kaiser Permanente selected the RAP foundation system for its "green" characteristics for medical offices.

ECONOMICS

While every building system is judged primarily by its performance and constructability, the system will not be used unless it also provides economic benefit to the owner. The RAP foundation system has been used in over 1,000 projects in the United States, with over 75 of those in California, on both private and public-owned structures. Because many public projects have published bid costs for base bids and their bid alternates, they provide examples of how much savings can be realized with RAP supported conventional shallow foundations.

Consider three different projects at the University of California at Davis (UCD). 1) For the West Entry Parking Structure, rammed aggregate piers where a bid alternate to belled concrete piers. According to public records, the reported savings was $950,000 for the RAP alternate over belled concrete piers. 2) RAP construction competed against straight concrete piers at the Mathematical Sciences Building, with $145,000 in reported savings. 3) At the Activities and Recreation Center, McCarthy Building Companies reported a $300,000 savings using RAP elements instead of a 10 foot massive excavation replaced with engineered fill base bid.

CONCLUSIONS

RAP construction is a ground improvement method for the support of conventional shallow foundations that has become well-accepted within the geotechnical and structural engineering communities. As demonstrated in this paper, engineers have another reliable foundation alternative to recommend for soft clay, loose silt and sand, undocumented fill, and generally poor and weak soil sites with demanding floor slab and foundation loads. With RAP supported footings, engineers can be assured of simplicity of design, good long-term performance characteristics, demonstrated constructability, and economic competitiveness.

RAP construction is successfully being delivered on both public and private projects throughout California. The case histories noted illustrate that the use of RAP soil reinforcement for the support of high bearing capacity footings resulted in cost savings within the same performance standards as other conventional deep and shallow foundation systems.

REFERENCES

Caskey, J.M. (2001). *"Uplift Capacity of Rammed Aggregate Pier Soil Reinforcing Elements."* Masters Thesis. University of Memphis. December 2001.

Farrell Design-Build Companies, Inc. (January 1999). *Block 224 Parking Garage Geopier Design and Construction Recommendations, Sacramento, CA.*

Farrell Design-Build Companies, Inc. (June 2000). *Corporate Headquarters - Geopier Design-Build Submittal, Dublin, CA.*

Fox, N.S. and Cowell, M.J. (1998). *Geopier Foundation and Soil Reinforcement Manual.* Geopier Foundation Company, Inc., Scottsdale, Arizona.

Hall, K.M., Wissmann, K.J., Caskey, J.M., and FitzPatrick, B.T. (2002). *"Soil reinforcement used to arrest bearing capacity failure at a steel mill."* Proceedings, 4th International Conference on Ground Improvement. Kuala Lumpur, Malaysia, 26–28 March.

Handy, R. L. (2001). "Does Lateral Stress Really Influence Settlement." *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 7.

ICBO ES Report ER-5916 (Reissued September 1, 2002) ICBO Evaluation Service, Inc. • 5360 Workman Mill Road, Whittier, California 90601 • www.icboes.org

Lawton, E.C., and Fox, N.S. (1994). *"Settlement of structures supported on marginal or inadequate soils stiffened with short aggregate piers."* Vertical and Horizontal Deformations of Foundations and Embankments, A.T. Yeung and G.Y. Fello (Editors), American Society of Civil Engineers, 2, 962-74.

Lawton, E.C., Fox, N.S. Fox, and Handy, R.L. (1994). *"Control of settlement and uplift of structures using short aggregate piers."* In-Situ Deep Soil Improvement, Proc. ASCE National Convention, Atlanta, Georgia. 121-132.

Lawton, E. C. (2000). "*Performance of Geopier Foundations During Simulated Seismic Tests at South Temple Bridge on Interstate 15, Salt Lake City, Utah*." Final Report, No. UUCVEEN 00-03, University of Utah, Salt Lake City, Utah.

Majchrzak, M., Lew, M., Sorensen, K., and Farrell, T. (2004). "*Settlement of Shallow Foundations Constructed Over Reinforced Soil: Design Estimates vs. Measurements*." Proceedings, Fifth International Conference on Case Histories in Geotechnical Engineering, April 13-17, 2004, New York, NY.

Minks, A.G., Wissmann, K.J., Caskey, J.M., and Pando, M.A. (2001). *"Distribution of Stresses and Settlements Below Floor Slabs Supported by Rammed Aggregate Piers."* Proceedings, 54th Canadian Geotechnical Conference. Calgary, Alberta. September 16–19.

Pitt, J.M, White, D,.J., Gaul, A., Hoevelkamp, K. (2003). *Highway Applications For Rammed Aggregate Piers In Iowa Soils.* Iowa DOT Project TR-443.

USGBC (2004) DPR-ABD Office Building, LEED #0480. LEED Version 2 Certification Level: Silver. http://www.usgbc.org/Docs/Certified_Projects/Cert_Reg115.pdf

Wissmann, K.J. (1999). "*Technical Bulletin No. 2 – Bearing Capacity of Geopier - Supported Foundation Systems.*" Geopier Foundation Company, Inc. Blacksburg, VA.

Wissmann, K.J., and FitzPatrick, B.T., and Lawton, E.C. (2001). *"Technical Bulletin No. 3 – Geopier Uplift Resistance."* Geopier Foundation Company, Inc. Blacksburg, VA.

Wissmann, K.J., and FitzPatrick, B.T., and Lawton, E.C. (2001). *"Technical Bulletin No. 4 – Geopier Lateral Resistance."* Geopier Foundation Company, Inc. Blacksburg, VA.