Rammed Aggregate Piers: Testing and Failure Modes

I recently had the opportunity to interview Richard Meyer, president of Shell+Meyer Associates, Ltd. Mr. Meyer has had many years of experience serving the Dayton area as a structural engineer. As such, it was a privilege to hear him comment on the significant advancements in structural engineering that have occurred during his career. Mr. Meyer has seen it all, from the introduction of ink plotters and the development of composite design to the proliferation of metal connectors in wood construction and post-tensioning in concrete construction. He also emphasized to me the technological advances in computing software. Of all the things that he mentioned, I would like to focus the topic of this essay on a more recent advancement: rammed aggregate piers.

Rammed aggregate piers (RAPs), sometimes referred to as the trademarked product Geopiers, are an innovated form of ground improvement. RAPs are used to economically increase the bearing capacity of soil under shallow foundations and slabs on grade. The typical method of RAP-construction begins with drilling a hole 2 or 3 feet in diameter 7 to 25 feet below the bottom of the footing (Shields 2004, p.461). A sleeve may be placed during drilling for soils susceptible to caving. Once the auger is removed, well-graded aggregate is added and compacted in 12-inch lifts. If a sleeve is employed, it is lifted out gradually in concert with the installation of the lifts. The aggregate is compacted using a beveled, convex hammer that compacts the aggregate vertically and also forces the aggregate horizontally, engaging the surrounding soil (Shields 2004, p.461). By also compacting the surrounding soil, this process increases the lateral pressure to approximately 90% of Rankine passive earth pressure (Suleiman 2006, p.391). For this reason RAPs effectively transfer load to the surrounding soil through skin friction. In fact, a RAP that is not loaded beyond its design limit will have transferred 75%-80% of its vertical load to the surrounding soil at a depth of two diameters (Suleiman 2006, p.396).

RAPs are typically installed in groups under spread footings or in a line under strip footings. In speaking with structural engineers who have designed footings on top of RAPs, I learned that they are instructed to consider RAPs, if spaced properly, as uniformly improving the soil bearing capacity. This simplification permits the typical methods of footing design. Improved bearing capacities after the installation of RAPs can range from 5,000 to 10,000 psf (Shields 2004, p.462). The extent of ground improvement that the RAPs provide is estimated by an experienced professional. To ensure the estimated ground improvement is met, a test cell is constructed on site. The test cell may be an RAP installed off to the side, or it may be an RAP that will eventually be under a footing. The test cell is installed with sensors that read stress at the tip and top of the RAP. Telltale rods protected by sleeves are connected to a plate above the bottom lift and inform the technicians of how much less the RAP tip settles in comparison to the concrete cap that tops the RAP. Loads are applied incrementally up to 1.5 times the design stress (Shields 2004, p.463). From plotting deflection vs. stress at the top of the RAP, a stiffness modulus is computed. The allowable soil pressure can then be calculated by multiplying the stiffness modulus by the allowable settlement.

The differential deflection and the stress at the tip of the RAP are important in determining if plastic deformation has occurred and if so, what failure mode is the source. Plastic deformation, or irreversible settlement, can occur in one of two ways. First, if the surrounding soil provides enough confining pressure to prevent “bulging” of the RAP (due to the Poisson effect) as the load is increased, the skin friction required to maintain vertical equilibrium will eventually exceed the shear capacity of the surrounding soil (Shields 2004, p.464). Shearing at the RAP-soil interface near the surface will permit
upper lifts to experience irreversible settlement as the tip begins to deform. After a limited amount of tip deformation, the tip will behave as all the other lifts and the RAP will continue to settle further into the soil as one unit. This mode of failure is known as tip deformation and occurs in RAPs with lower slenderness ratios (length/diameter) (Suleiman 2006, p.389). With this mode of failure the plots of settlement vs. stress for the top and the tip of the RAP will both exhibit two distinct linear sections. The first linear section corresponds to the elastic deformation and is the portion used in determining the stiffness modulus. The second linear portion corresponds to the plastic deformation and exhibits a greater slope. The transition between the two linear portions is identified as the design stress limit. Note that in Figure 1 the top of the RAP exhibits a change in slope slightly before the bottom does as indicated via the tell-tales.

![Figure 1: Typical Settlement vs. Stress of Tip Failure Mode](image1)

The other mode of failure is known as bulging. With this latter mode only the data corresponding to the RAP top produces a distinct transition from elastic to plastic deformation. As seen in Figure 2, the tip of the RAP does not exhibit a distinct design stress limit because the plastic deformation is limited to the upper portion of the RAP as it bulges outward radially into the surrounding soil (Shields 2004, p.464). This latter mode of failure is common with RAPs in cohesive soils that provide little confining stress and in long, slender RAPs in granular soil.

![Figure 2: Typical Settlement vs. Stress of Bulging Failure Mode](image2)

Shell+Meyer has used RAPs in many of their projects. Of particular interest was their use of RAPs in the construction of the GE Aviation EPISCenter on the campus of the University of Dayton. Shallow foundations had been selected due to the site conditions: contaminated soil existed below a top layer which had already been remediated, and any excavation below this would incur costly remediation services. In this situation traditional RAPs would require drilling into the contaminated layer, producing contaminated spoils. To avoid this Shell+Meyer utilized displacement RAPs. For this
type of ground modification a casing is driven into the ground to the desired depth. The end of the casing is capable of opening at depth and the lifts are installed as the casing is slowly removed. In this way the displacement RAPs provide all the benefits of traditional RAPs without producing any spoils.

Rammed aggregate piers are an innovative and cost effected method of ground improvement. They can be designed to meet specific improvement criteria and alternative methods of installation provide potential cost savings. It is important that a structural engineer understand the installation and testing procedures of rammed aggregate piers as well as their load transfer mechanism and failure modes before selecting RAPs as a method of ground improvement.

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