



**T**he demand for new roadway construction or expansion of existing infrastructure for both public and private owners continues to grow. These projects commonly involve grade-separation construction and projects are often restricted by tight schedules, limited funding, public opposition, and right-of-way limitations, among other things. Although project challenges may vary, one universal question remains for engineers, contractors, and owners on every project: How do you design and build the project to meet the owner's cost and schedule requirements?

Infrastructure construction involving grade separations in urban environments is often challenged by tight or difficult access and limited right-of-way restrictions for construction. As an alternate to sloped embankments, which typically require large work areas and property acquisition, grade-separation solutions typically involve construction of retaining walls using either conventional cast-in-place concrete cantilevered walls or mechanically

stabilized earth (MSE) walls. While both systems are commonly used, many public and private owners have adopted MSE wall solutions, which represent a more economical and faster wall construction approach than cast-in-place cantilevered retaining walls. MSE walls can also be designed to tolerate more settlement.

However, weak or compressible foundation soils present significant design and construction challenges. Wall heights commonly range from 10 to 40 feet and apply pressures ranging from 4,000 to 7,000 pounds per square foot (psf) near the wall face, depending on the specific wall design. The increasing size of these walls poses geotechnical challenges, including inadequate factors of safety for global stability and bearing capacity, as well as excessive total and differential settlement.

Traditional solutions for remedying

## Designing strong walls on weak soils

**Civil engineers have options to remedy foundation soil problems and meet project cost and schedule requirements.**

By Fadi Faraj, P.E.; Michael H. Garrison, P.E.; and Brendan FitzPatrick, P.E.

foundation soil problems include massive overexcavation and replacement, deep foundations, or staged construction. Each of these options provides distinct advantages and disadvantages and is selected based on the project-specific needs.

For instance, overexcavation is most commonly used when the depth of weak or compressible soils is relatively shallow (less than 10 feet). Removal of shallow, unsuitable soils and replacement with compacted, engineered fill is often an inexpensive approach to provide improved foundation soils in these conditions. Overexcavation and replacement may become less cost-effective, however, when poor soils extend to deeper depths, dewatering is required because of shallow groundwater, temporary shoring is required to stabilize an excavation next to an existing roadway, or the presence

**Construction of cantilevered or mechanically stabilized earth retaining walls to create grade separations presents significant design and construction challenges when faced with weak or compressible foundation soils.**

## RETAINING WALLS ▶



Rammed Aggregate Pier installation involves drilling a 30-inch-diameter hole; placing thin lifts of aggregate within the cavity; and vertically ramming the aggregate using a high-energy, patented beveled impact tamper.

of contaminated soil results in high costs of disposal. Overexcavation and replacement is significantly affected by inclement weather, which could present schedule challenges as well.

When compressible or weak soils extend to depths of 30 or 40 feet or greater, options for supporting embankments or wall construction may include staged construction or deep foundations. Staging involves embankment construction to specific heights, temporarily stopping construction and monitoring the embankment until settlement is complete, followed by continuation of construction to greater heights. The purpose is to build the embankment to specific heights where the existing soils will provide suitable support. As the new embankment

pressure is applied, settlement occurs and the weak foundation soils become stronger, thereby permitting higher embankment construction. This process is repeated in multiple stages until the embankment reaches the final design height. This approach is well suited when there is significant time in the construction schedule. This approach is not often a viable solution when the embankment construction is part of the critical path for the project.

Deep foundations are used in similar situations with deep, compressible soils to support and transfer the embankment pressures to more competent bearing layers. Deep foundations are

able to support high loads through very soft soils — delivering superior performance — but are an expensive solution. The costs incurred include not only the deep foundations (driven steel or concrete piles, augercast-in-place piles, or caissons) but also a load-transfer platform constructed using either multiple layers of structural geogrid or a concrete mat to transfer embankment pressures to the deep foundation elements.

The balance of cost, schedule, performance, and ease of construction has led design teams to an alternative approach for embankment and wall construction called an Intermediate Foundation solution. This approach uses Rammed

## RETAINING WALLS ▶



Retaining wall heights commonly range from 10 to 40 feet and apply pressures ranging from 4,000 to 7,000 pounds per square foot near the wall face, depending on the specific wall design.

Aggregate Pier (RAP) systems to reinforce poor soils to intermediate depths, typically ranging from 10 to 40 feet (see Figure 1). As described in the recently published Highway Innovative Technology Evaluation Center (HITEC) evaluation report, RAP elements use highly densified aggregate piers to improve the composite engineering characteristics of poor or unsuitable soils to support high applied pressures. Installation involves drilling a 30-inch-diameter hole; placing thin lifts of aggregate within the cavity; and vertically ramming the aggregate using a high-energy, patented beveled impact tamper.

During construction, the high-frequency energy delivered by the modified hydraulic hammer, combined with the beveled shape of the tamper, not only densifies the aggregate vertically to create a stiff aggregate pier with internal friction angles on the order of 50 degrees, but also forces aggregate laterally into the sidewall of the hole, resulting in lateral stress increase in surrounding soil. The lateral stress increase

reduces the compressibility of the surrounding soil and promotes positive coupling of the RAP element and the soil to create a composite, reinforced soil zone.

Additionally, when constructed using open-graded stone, the RAP elements act as vertical drains to promote radial drainage and accelerate settlement within the reinforced zone. Overall, the system provides the benefits of increased shear resistance for stability and bearing capacity improvement coupled with reduction in settlement magnitude and duration by improving the strength and stiffness of soft or compressible soils at intermediate depths.

### Foundation challenge

Engineers designing the Loop 363 South Interchange project in Temple, Texas, were confronted by design challenges for a series of new grade-separation walls — inadequate factors of safety for global stability and bearing capacity, as well as excessive total and differential settlement. The project involved reconstruction of portions

of Loop 363 to create a new highway interchange along Interstate 35, as well as widening nearby portions of Loop 363 to accommodate the traffic demand created from the new interchange.

In one location, an existing embankment was used to facilitate a grade separation over an existing railroad crossing. The plan called for widening the existing two-lane roadway to accommodate a total of four lanes. In another location, proposed interchange construction required new grade-separation construction. Because of the presence of a nearby telecommunication substation, acquiring additional right-of-way to facilitate widening of the existing embankments was not a viable solution. After a preliminary analysis was conducted to compare construction of an extended bridge with an embankment/retaining wall, the project team concluded that a taller MSE wall would be the most economically feasible solution.

Led by transportation engineers at PBS&J working for the Texas Department of Transportation, the project team developed plans for walls as high as 38 feet at a railroad overpass and as high as 22 feet at the new I-35 interchange. Wall construction was expected to apply pressures greater than 4,250 psf at the 22-foot-tall wall and 7,500 psf at the 38-foot-tall wall.

Geotechnical engineers at HVJ Associates, Inc., investigated existing soil conditions at the wall locations and evaluated performance of the walls. Soil conditions for the project consisted of newly placed clay fill, in some areas extending to depths of about 8 feet, underlain by very soft to stiff clay. The clay ranged from low to high plasticity, with moisture contents ranging from 15 percent to 38 percent. The clay was

Weak or compressible foundation soils present significant design and construction challenges.

underlain by bedrock at depths as shallow as 13 feet in some locations and more than 30 feet in other locations.

HVJ Associates identified early in the design that construction of the tall walls would result in significant increase in the shear stress (demand) on the underlying weak clay foundation soils. In addition, the high applied pressures at the wall face resulted in unacceptably low factors of safety for bearing capacity. While settlement control was less of a concern in areas with shallow rock, the high wall pressures applied in areas of deeper rock were expected to result in unacceptable long-term settlement.

Using conventional limit equilibrium

analyses (slope stability programs), HVJ Associates concluded that the shear strength (resistance) along the critical slip surface extending behind the reinforced portion of the wall and through the weak clay was insufficient for supporting the walls. Factors of safety for stability may be determined as the ratio of the shear strength within the contributing soil layers along the slip surface to the applied shear stress. The calculated factor of safety for the long-term case was less than 1.25 for walls taller than 15 feet, and approximately 1.0 for walls taller than 20 feet, indicating a strong likelihood of global instability.

Bearing pressures were calculated at the retaining walls and, using conventional Terzaghi bearing capacity approaches, engineers determined that the factors of safety for bearing would fall below the required minimum factor of safety of 2.0 for wall heights greater than about 16 feet. While settlement in the areas with relatively shallow rock was less of a concern, the variability of the clay stiffness and the deeper depth to rock coupled with the high design pressures resulted in estimated post-construction settlement of more than 5 inches. An alternative solution was required to limit the post-construction settlement to 1 inch or less.

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The conventional approach of removal and replacement was initially considered by the design team to address the geotechnical design challenges. Concern about required depth and lateral extent of excavations combined with negative impacts to the construction schedule and costs led the project team to consider other alternatives. Based on previous project experiences, engineers from HVJ Associates determined that an Intermediate Foundation solution using RAP elements would provide the level of improvement required to satisfy factors of safety for both bearing and global stability and provide sufficient improvement in the composite stiffness to control settlement of the walls. The system would also provide a cost-effective approach to soil reinforcement while making short work of pier installation.

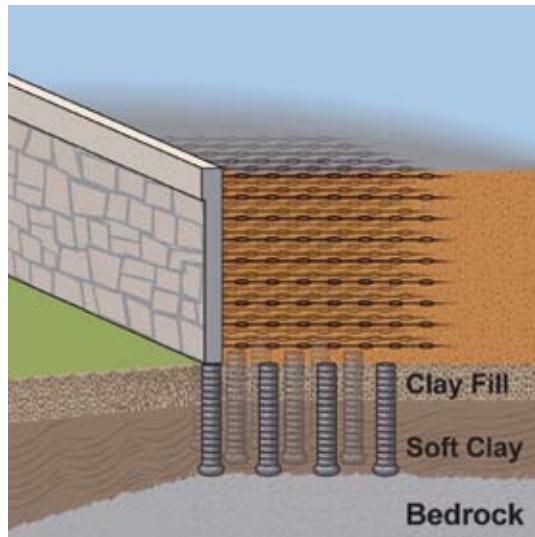


Figure 1: Conceptual drawing of mechanically stabilized earth wall Rammed Aggregate Pier element layout

elements installed beneath the MSE walls. RAP spacings ranging from 4.75 to 8.5 feet on-center were incorporated beneath wall heights of 16 feet or greater. The spacing of the piers was reduced, corresponding to increases in wall heights, to provide sufficient levels of improvement. Piers were as long as 16 feet but did not completely penetrate the clay. In some locations, piers did tag the shallow rock.

By incorporating the high shear strength afforded by each pier, the improved strength characteristics of the composite reinforced zone provided increases in the factors of safety for bearing capacity instability and global

### Design and installation

Working closely with the project team, a solution was developed by Geopier Foundation Company, Inc., consisting of two to four rows of RAP

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instability to greater than 2.0 and 1.3, respectively. Additionally, the stiff RAP elements substantially reduced settlement magnitudes to meet the stringent post-construction settlement requirement.

Working for general contractor Zachry Construction Corporation of San Antonio, Texas, Peterson Contractors, Inc., of Reinbeck, Iowa, installed the piers. During installation, field monitoring was performed to provide quality control for the installations. In addition, field performance verification of the RAP system was accomplished by conducting a full-scale modulus test.

The modulus test is similar to a pile load test, where stress is applied to a concrete cap at the top of the pier using a 100-ton jack reacting against a steel beam held in place with helical anchors. Deflections are taken to monitor the movement of the top of the pier.

Additionally, a steel telltale rod sleeved in PVC and installed within the pier allows for deflection measurements near the bottom of the pier. By monitoring deflections at both the top and bottom of the pier, the modulus test provides confirmation that the stiffness of the pier achieves the required design stiffness, and that the pier is sufficiently long to dissipate stress to act as an intermediate foundation as opposed to a deep foundation (pile), which transfers loads to a better layer. The modulus test results showed a total movement of 0.69 inches at a stress of more than 22,000 psf, indicating a pier stiffness greater than twice the assumed design value.

### Conclusion

Solutions to address the engineering challenges encountered on transportation projects must first overcome the technical challenges. Cost-effective-

ness and impacts to the construction schedule must then be considered when evaluating the overall effectiveness of a solution to reinforce poor foundation soils. Each project requires a unique solution to address the specific design challenges such as global instability, inadequate bearing, or excessive settlement magnitude or duration. ■

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