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Short Aggregate Piers Reinforce Soils Near Tunnels

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Abstract

Short aggregate piers (Geopier™ foundation elements) were used to reinforce loose, collapsing sand and clay soils over and around an existing railroad tunnel. During construction, an unbraced corrugated steel plate arch tunnel lining had deformed laterally under pressure from sand backfill, leaving voids along the lower tunnel walls. In time sand slowly infiltrated into the voids from above, causing the road and sidewalk slabs to settle and tilt approximately 150-200 mm (6-8 inches) downward from the crest of the tunnel. The damaged slabs were removed, and soil near and over the tunnel was laterally compacted and reinforced with short aggregate piers prior to slab replacement. Based in part on these results, an option was suggested to use compacted short aggregate piers to help reduce stresses induced by foundations for a new building over a 90-year-old sewer tunnel.

A supplemental influence from compaction of short aggregate piers may be to increase resistance to soil liquefaction during earthquakes. Total energies are comparable to those from deep dynamic compaction, and have the advantage of being distributed throughout the length of the pier instead of being concentrated at the ground surface. The maximum depth of influence is about 4.5m (15 ft).

Introduction

Short aggregate piers (Geopier foundation elements) and the associated matrix soil

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normally are used to support buildings and other structures. This is the first reported use as soil reinforcement around tunnels and for pavement support.

The Problem

It was not the most momentous construction project in Madrid, Iowa (pop. 2526), and not as exciting as when the school burned down earlier in the week, but the new railroad tunnel underpass did contribute an element of surprise after the street on either side settled so much that an unsuspecting driver easily could go airborne and land on the other side in a series of spine-jarring bounces. As the street barricades went up, a local wryly observed, "I don't mean to pry, but is that really the way this is supposed to be?"

Investigation

The corrugated steel plate arch tunnel replaced a turn-of-the-century railroad overpass bridge. Unfortunately, as the unbraced tunnel was being backfilled, lateral soil pressures pushed the sidewalls inward (Figure 1). After construction, soil on either side of the tunnel crest gradually settled, creating a pavement geometry like a shallow roof with a peak in the middle. Faced with an untenable situation, the contractor took bankruptcy and left others to work out the deficiencies.

A post-construction geotechnical report described loose sand fill to the depth of the borings, 3 m (10 ft), on both sides of the tunnel, and attributed the excessive settlement to inadequate compaction. However, this did not explain the narrowed and lopsided shape of the tunnel. The construction specifications had called for temporary bracing to be installed to hold the tunnel shape while the fill was being placed, and apparently through ignorance of the magnitude of the potential damage from lateral soil pressures, the bracing was omitted.

Figure 1. Installing compacted short aggregate pier reinforcing members along a deformed railroad tunnel.

The distortion shown in Figure 1 suggests that backfilling may have proceeded first on the south (right) side, pushing the top of the tunnel to the north. Then as would be expected, filling on the north side then did not overcome passive pressures and push the tunnel lining back, but only caused the sides to deform inward. That in turn would tend to create voids next to the lower walls of the tunnel lining as they were pushed away from the previously compacted backfill. Thus, because of the lack of temporary tunnel bracing, soil compaction may have aggravated instead of preventing the future settlement problem.

The hypothesis concerning distortion of the tunnel lining during backfilling was supported by observations of a high groundwater table in sand backfill close to the tunnel, perhaps attributable to upward displacement by sand falling down into the lower, water-filled voids. Groundwater mounding was contained on one side by the tunnel lining and on the other by clay soil, and at the ends by a concrete facing that was added to prevent slope erosion (Figure 1).

Repair options

An early clue that the problem might be serious and ongoing was when lower walls flanking the ends of the tunnel pushed in, in part because of the lack of a resisting top arch. A repair was made by tying back the end walls with horizontal ground anchors. While these appeared to stop further inward movements of tunnel walls, they did not stop pavement settlements.

The most obvious repair option for the tunnel itself was to start over, removing the pavement slabs and approach fills, re-shaping and bracing the tunnel lining, and replacing and compacting the backfill. Disadvantages of this procedure were high cost, a long construction time during which rail traffic would be interrupted, and sensitivity to weather conditions. Another option, structural slabs supported on piles and grade beams, would be an expensive overkill.

The thickness of soil cover over the tunnel was about 1.2 m (4 ft), too thin for geofabric reinforcement to have much effect. Furthermore, the depth and extent of collapsible soil next to the tunnel indicated that a deeper method of soil improvement was needed. Pressure grouting would be difficult because of ready escape routes through sides of the embankment.

It therefore was decided to compact and reinforce the existing loose backfill with specially compacted short aggregate piers (Geopier foundation elements) that densify the soils adjacent to the piers and increase lateral stresses in the soil matrix, aiding the transfer of surface pressures away from the tunnel walls. One possible disadvantage would be a tendency to further warp the tunnel lining during installation and lateral compaction of the piers. This disadvantage was mitigated by the restraining weight of the soil in place over the tunnel, a situation that was unlike that of the initial backfilling. Additionally, observations of the tunnel were made during pier installation to allow procedures to be changed if problems should arise.

Horizontal stresses

Horizontal in-situ stress measurements at other sites with the K_o Stepped Blade (Handy et al. 1982) indicate that Geopier compaction can impose limiting passive conditions in soils close to the aggregate piers, with lateral pressures dissipating linearly with radial distance outward from each pier. The lateral stress regime extends approximately one diameter below the drilled depths of the piers prior to compaction.

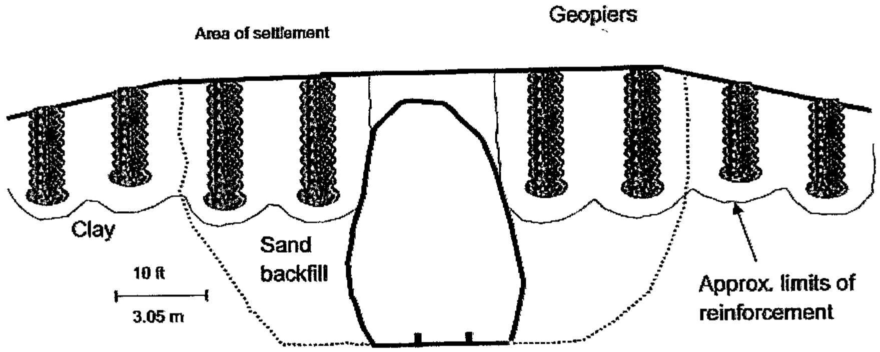

Figure 2. Pier positions relative to the tunnel. Compaction expands the aggregate piers downward and laterally, compressing and stabilizing the encompassing soil.

Design

The distorted tunnel was approximately 7.3 m (24 ft) high, so two lines of 760 mm (30 inch) diameter by 3.6 m (12 ft) long piers were constructed in the sand backfill on either side of the tunnel to extend down to near the spring line, in order to densify the soil and transfer load to the tunnel arch (Figure 2). These two primary lines were flanked by two additional lines on each side extending to 3 m (10 ft) depth, thereby creating a reinforcing layer in the shape of shallow flanking arches pointing slightly downward towards the tunnel lining. Each line is comprised of five piers, giving a total of 40 compacted short aggregate piers spaced 2.4m (8 ft) and 1.5m (5 ft) apart parallel and transverse to the roadway, respectively.

Figure 3. Dumping a pre-measured amount of aggregate that when compacted will comprise a single lift in the pier.

A bulb of free-draining, coarse aggregate was rammed at the bottom of each pier. Previous studies have shown that the additional depth of densification approximately equals the diameter of the pier, but in loose sand susceptible to vibration the influence may extend deeper. An open-graded aggregate was selected for the basal bulb to reduce the potential for excess pore pressure and even possible liquefaction of the sand.

A special circular ram beveled at 45° around the perimeter is used to induce lateral compaction and high lateral stresses in soil between and adjacent to the piers. The ram used for 760 mm (30-inch) piers is 660 mm (26 in.) in diameter, with the bevel occupying over 50 percent of the surface contact area.

The normal compaction procedure is to ram the basal bulb for 1 minute or to refusal, after which the pier is built up in nominal 300 mm (1 ft) thick layers of well-graded aggregate, each layer being compacted for a minimum of 20 seconds and to refusal with a 400-600 cycle per minute hydraulically driven ram. A discussion of the total energy involved is presented later in this paper.

Construction

Temporary casing was required for pier borings in the sand backfill to prevent collapse into the open borings. The casing was incrementally pulled upward prior to dumping and ramming each aggregate layer (Figures 3 and 4). Casing was not required for borings in the

Figure 4. Special beveled ram being lowered through the temporary casing to compact the next layer of the aggregate pier.

Results

Future deflections of the pavement slab are predicted to be less than 25 mm (1 inch), and the reinforcement appears to be performing satisfactorily.

A tentative tunnel application with a different focus

New construction in an old city often impinges on older—in some cases much older—buried structures that still are functional and in use. Such is the case in Memphis, Tennessee, where a 1.8x1.5 m (5x6 ft) inside-dimension concrete sewer tunnel constructed prior to 1914 underlies the site of a planned multistory commercial building.

Test borings revealed 2 to 8 m (6 to 27 ft) or more of random fill over and around the 90+ year-old tunnel that still is in service. Historical maps indicate that the tunnel was constructed along an old bayou that was filled to match adjacent grade elevations. Construction options included moving the tunnel, or leaving it in place and defending it from the anticipated foundation loads. For reasons of economy and scheduling the latter procedure was selected.

The tunnel will be structurally strengthened and is being lined internally. One option is to strengthen and reinforce the overlying fill with compacted short aggregate piers. In contrast to piling, these would not extend down to the level of the tunnel, but as in the

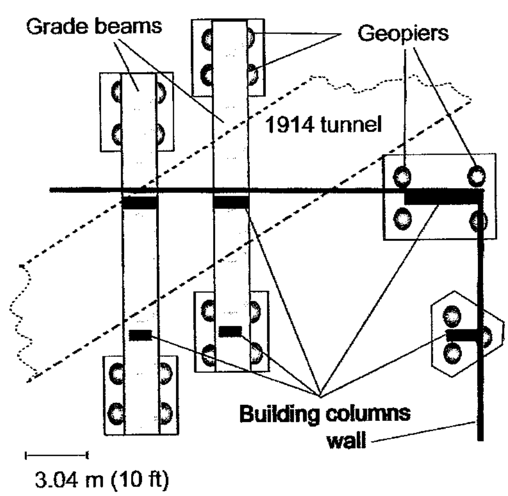

Figure 5. Support members and grade beams to protect an existing tunnel from anticipated foundation loads.

case of piling they would not be installed directly over the tunnel, but off to the sides, where groups of three or four, nominal 760 mm (30 inch) diameter, 2.1 m (7 ft)-long piers and the associated soils are planned to support concrete pads that in turn will support grade beams and footings for the building (Figure 5).

Calculated transfer of pier compaction stresses to the tunnel

A potential drawback to the use of rammed aggregate piers is the dynamic tamping force. A force of 260 kN (60 kips) has been measured at the base of the 0.45 sq m (4.91 sq ft) tamping foot, giving a tamping stress of 580 kPa (12,000 psf) at the contact with the soil (Lawton, 1998). This of course will vary depending on dynamic properties of the soil. From elastic theory and based on an influence factor of 0.02, the maximum dynamic stress transmitted to the tunnel during compaction will be approximately 12 kPa (250 psf). This is over twice the static load pressure that will occur from the aggregate pier-supported building. Thus the pier compaction may be regarded as a proof test of the tunnel structure, in which case the tunnel will be inspected before, during, and after pier installation. Based on elastic analysis of the stress distribution and on experience, settlement of the completed building structure is anticipated to be less than 25 mm (1 inch). If another option such as the use of drilled shafts is selected to support the grade beams, a small amount of differential settlement therefore may be expected.

Rammed aggregate piers to improve earthquake resistance

Memphis is near the New Madrid, Missouri epicenter of some of the largest earthquakes recorded in North America. Four earthquakes of about magnitude 8 occurred within this seismic zone during the winter of 1811-1812. The New Madrid region constitutes the highest level of seismicity in the central and eastern parts of the US. A peak ground acceleration of 0.3-0.35 g is associated with an earthquake that has a 5 percent probability of being exceeded in 50 years (USGS, 1998).

Compaction of short aggregate piers is somewhat analogous to the deep dynamic compaction (DDC) ground improvement method. The DDC method consists of densifying the soil be repeatedly dropping a heavy weight from a crane, and has been shown to be effective for densifying potentially liquefiable soils to depths of about 10-12 m (30-35 ft) (Broms, 1991). A simplistic view is that dynamic compaction creates localized ground vibrations that do the same job as earthquakes, prior to building on potentially unstable ground.

A disadvantage of the DDC method is that high levels of energy must be applied at the ground surface in order to densify soils at depth. The maximum compaction depth varies with the square root of the impact energy, so doubling the impact energy increases nominal penetration depth only by $\sqrt{2}$ (Broms, 1991). High ground surface energy levels induce relatively large peak particle velocities that may be damaging to brittle structures, which of course includes old concrete tunnels.

The energy level per stroke during construction of 760 mm (30 inch) diameter aggregate piers is about 5 kNm (3700 ft-lb), roughly a thousand times less than typical energy per blow with DDC. On the other hand, whereas 3 to 8 blows are typical at each location with DDC, over 3500 blows will be delivered to construct a 3.7 m (12 ft) long aggregate pier. Thus the total energy inputs are of the same order to magnitude. However, compaction energy for the piers is applied almost uniformly throughout the length of the pier. Of particular importance is that the distributed, lower impact compaction should significantly reduce the risk of damage to nearby structures.

In contrast to the positive depth control from the use of the rammed aggregate method, the penetration depth of DDC (in meters) varies from 0.3 to 0.8 times $\sqrt{WH}$, where W is in tonnes and H is in meters (Broms, 1991). Thus, to attain a compaction depth of 3.7 m (12 ft), a 10 tonne weight would be dropped from 2 to 15 m, depending on the soil conditions.

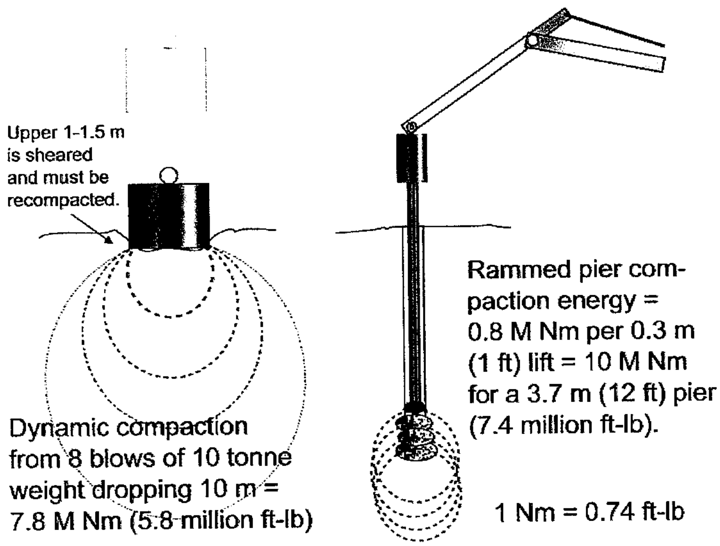

Figure 6. Compaction energies are comparable to reach a comparable depth, but pier compaction is more uniform and gives better depth control.

Additional earthquake protection will derive from the removal of compressible materials and replacement by densified aggregate. Recent research by Lawton (1998) with instrumented full-size short aggregate piers on an Interstate Highway 15 bridge section in Salt Lake City, Utah, indicates that Geopier-supported footings moved only a few millimeters (fractions of an inch) after being subjected to over 60 push-pull cycles simulating loadings from a magnitude 7.5 Richter scale earthquake. Static load tests indicate that aggregate piers are substantially stiffer than stone columns, attributable to the higher degree of compaction. Hydraulic conductivity of the piers varies depending on gradation of the aggregate, an open gradation being preferred where there is a possibility for either positive or negative pore pressures developing during or after compaction.

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