STRUCTURAL BREADTH STUDY

Intermediate, Geopier-reinforced Mat Slab versus Deep Micropile Foundation System

Introduction

This analysis examines the feasibility of replacing the existing deep micropile foundation system with an intermediate solution of soil-reinforcing, rammed aggregate piers in combination with a mat slab foundation. A breadth analysis of the proposed structural system will be demonstrated through calculations on the soil reinforcement strategy as well as the design of the mat slab for three zones of the building. This is followed by a comparative analysis of the proposed versus existing systems, with emphasis on three core areas of project management- constructability, schedule reduction, and value engineering.

Existing Conditions

The Cancer Institute building is supported by a micropile foundation system in combination with cast-in-place piers and grade beams. The design employs the same system used by the nearby Parking Garage project at PSHMC, scheduled to be completed in June 2007. The structure is supported by load-bearing micropiles that are drilled into the ground approximately 70 feet, surrounded by a metal casing. The piles require 10 to 20 feet of bonding length in stable rock to resist uplift and shear forces. When the bond zone has been located, the casing is filled with grout that adheres to the threaded piles. Pile caps, column piers and grade beams are formed and placed atop these micropiles to support load-bearing walls and columns. At the Cancer Institute, non-load bearing walls and frost walls will utilize conventional shallow footings.

The issue that arises with the micropile system is the ability to find competent rock at reasonable depths. Central Pennsylvania is considered primarily karst topography; limestone-derived soil which is vulnerable to weathering. The soils at PSHMC are no exception. At the Parking Garage project in particular, significant setbacks occurred as a result of micropiles being drilled, on average, 20 feet deeper than originally estimated in order to be set in a suitable rock. Compounding this problem was the fact that a minor fault line crosses the back of the site, causing extremely poor rock zones for any pile placement. Several piles were being drilled anywhere from 120' to 300' before ever-reaching a competent 20' of stable rock. As if this wasn't enough, several sinkholes developed during the process. In one case, a drilling team was forced to stand over a deep fissure sinkhole with the aid of wooden planks so they could finish placing a pile.

The Parking Garage project took significant losses both in schedule and cost. As the average pile depth climbed, multiple meetings had to be called involving all of the project entities. Eventually it was decided to cease drilling if a pile exceeded 120', at which point the structural engineer would redesign the pier or grade beam in that area. In all, about 20 piles were added, pile caps were enlarged and two adjacent piers were combined to form a combined footing. The extensive redesign not only halted production rates but also created a time-consuming feedback loop whenever piles exceeded the 120' maximum. When the last element was placed, the $2 million dollar pile job incurred a change order totaling $600,000. The micropile placement schedule, originally scheduled to take 73 days, ended up lasting 109 days- a 49% inflation.

Figure 1. View of Parking Garage project from CI site

Problem Statement

Unforeseen subsurface conditions can be extremely detrimental to a project, as realized by the Parking Garage. The fact that the Cancer Institute is only a short distance from this site presents the possibility that it will experience a similar setback with its deep foundation system. As the early phasing sequence of site improvements incurred its own delays, further setbacks of this magnitude can not be tolerated on the project.

Research

Analysis began by compiling a list of possible alternatives to the micropile system, with the first source being the geotechnical report. The engineers initially considered spread and continuous footings in conjunction with soil reinforcement techniques, but this presented settlement and future sinkhole issues. Keeping their suggestions in mind, a side-by-side comparison of possible alternatives was drawn up.

Figure 2. Possible Foundation Alternatives

System / Criterion	Mat Slab Only	Caissons	Engineered Fill with Mat Slab	Soil Reinforcement
Cost	Expensive	Very Expensive	Moderate	Moderate
Schedule	Slow- extensive rebar placement	Very Slow- Up to 72" diameter	Moderate	Fast
Benefits	Good in bad soils; simple design (2-way slab); Place during daytime	Little settlement; minimal vibration	Avoids deep foundations; no water table issues	Permanent lateral soil stress; Cheap and Quick
Drawbacks	Differential settlement; sinkholes over time; availability	Time consuming; Place at night (ED Sensitivity)	Adjacent spaces; added earthwork costs	Limited by load they carry; Place at night
Feasible?	Needs More Review	No	No	Needs More Review

As seen above, a mat slab foundation system alone will not be suitable for the Cancer Institute. Differential settlement needs to be minimized due to the sensitivity of the spaces and equipment, as well as to avoid issues at the Emergency Delivery and future Children's Hospital connections. Caissons, though supporting the existing hospital, are simply too costly. In reality the only feasible alternative was soil reinforcement, which was mentioned in the geotechnical report but not described in detail.

After researching soil reinforcement technologies further, it became apparent that stone columns, installed either through vibratory or auger placement, could strengthen the soil enough to enable a mat slab foundation (see Figure 3). One company in particular, Geopier Foundation Company, Inc., has a patented system of rammed aggregate piers (RAPs) that is for the Cancer Institute project in terms of pile substitutions. Geopiers were used for the recently completed 7,800 square foot Oncology Treatment Building at PSHMC in lieu of conventional stone columns. Thus, the idea evolved to replace the deep foundation system with a Geopier-reinforced mat slab, essentially an intermediate design. Research also considered the use of excess fill on PSHMC's campus to surcharge the site for a few months prior to the foundation start date. However, this was soon eliminated due to the fact that it was not substantial from a cost-benefit perspective. To have any lasting impact on soil stability the surcharge would require years rather than the few summer months available.

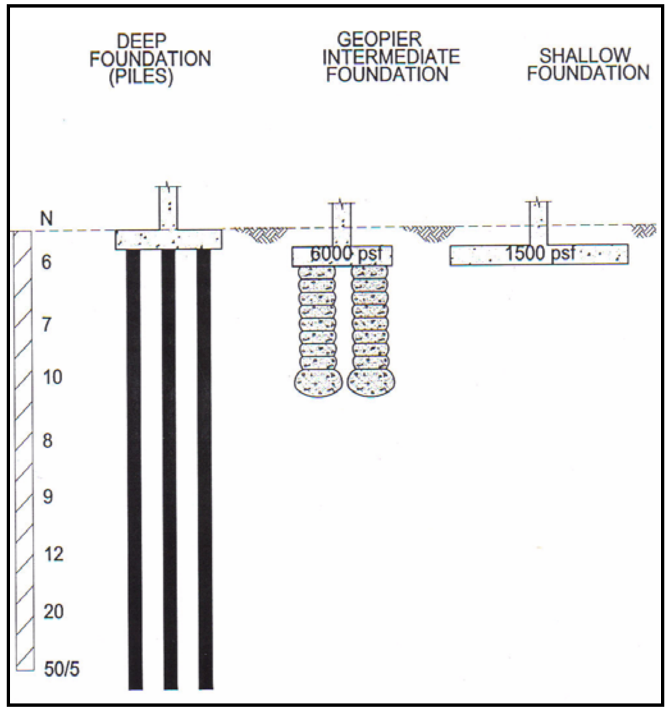


Figure 3. Foundation Alternatives- Bearing Strengths

Proposal

In order to avoid any subsurface conditions associated with deep foundation systems, I propose to replace the existing system with soil-reinforcing Geopier™ rammed aggregate piers that will support a large mat slab across the site. The remainder of this study contains structural and construction-related analyses comparing this system with the existing micropile design.

Structural Analysis

As the proposed system contains two key elements, calculations required a unique approach. The scope and complexity of this redesign requires several assumptions to achieve this uniformity:

- Two separate analyses will be performed:
    - Geopier-supported shallow foundation (GeoStructures Manual)
    - Mat slab only (Feasibility analysis)

- Analysis divides building footprint into three zones with uniformly distributed loads (illustrated on next page):
    - Zone 1- Primary Area (36,733 sf)
    - Zone 2- Radiotherapy Vaults (6,000 sf)
    - Zone 3- Shell Space (13,811 sf)

The assumptions employed in these structural calculations should be considered baseline values used to perform a meaningful design and construction-related analysis.

Geopier Mechanics

Geopiers work by pre-stressing soils both vertically at the bottom of the cavity, and horizontally during subsequent compaction of thin aggregate lifts. The RAPs in particular are beneficial in that they reduce both total and differential settlement because of their high strength and stiffness. Projects using this type of soil reinforcement typically employ a grid design to achieve homogenized results. Due to the fact that the Geopier elements are stronger than in-situ soils, it creates bending stresses in the slab between piers. Thus, floors must be treated as two-way slabs rather than a typical slab on grade.

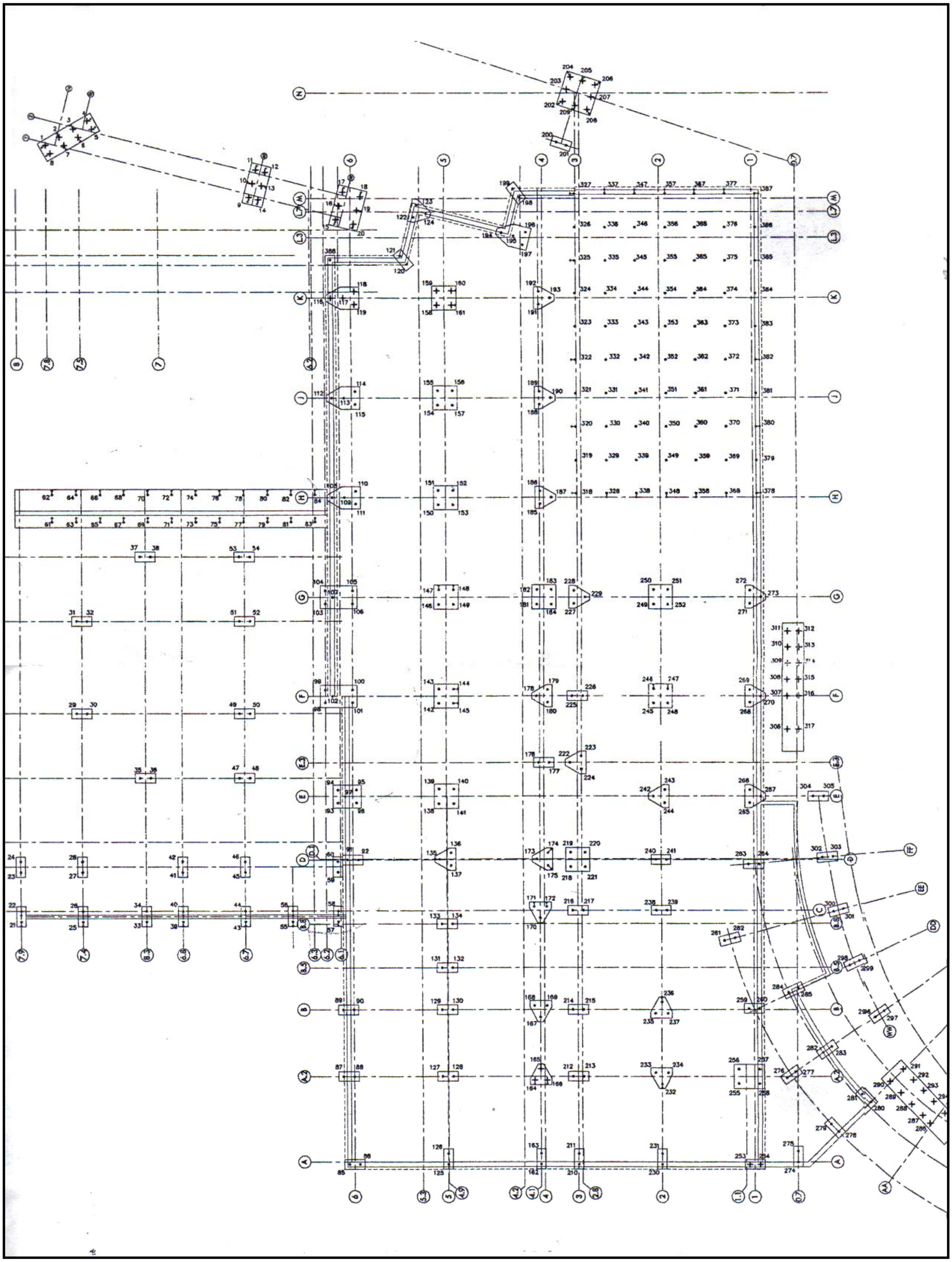
Geopier Calculation Results

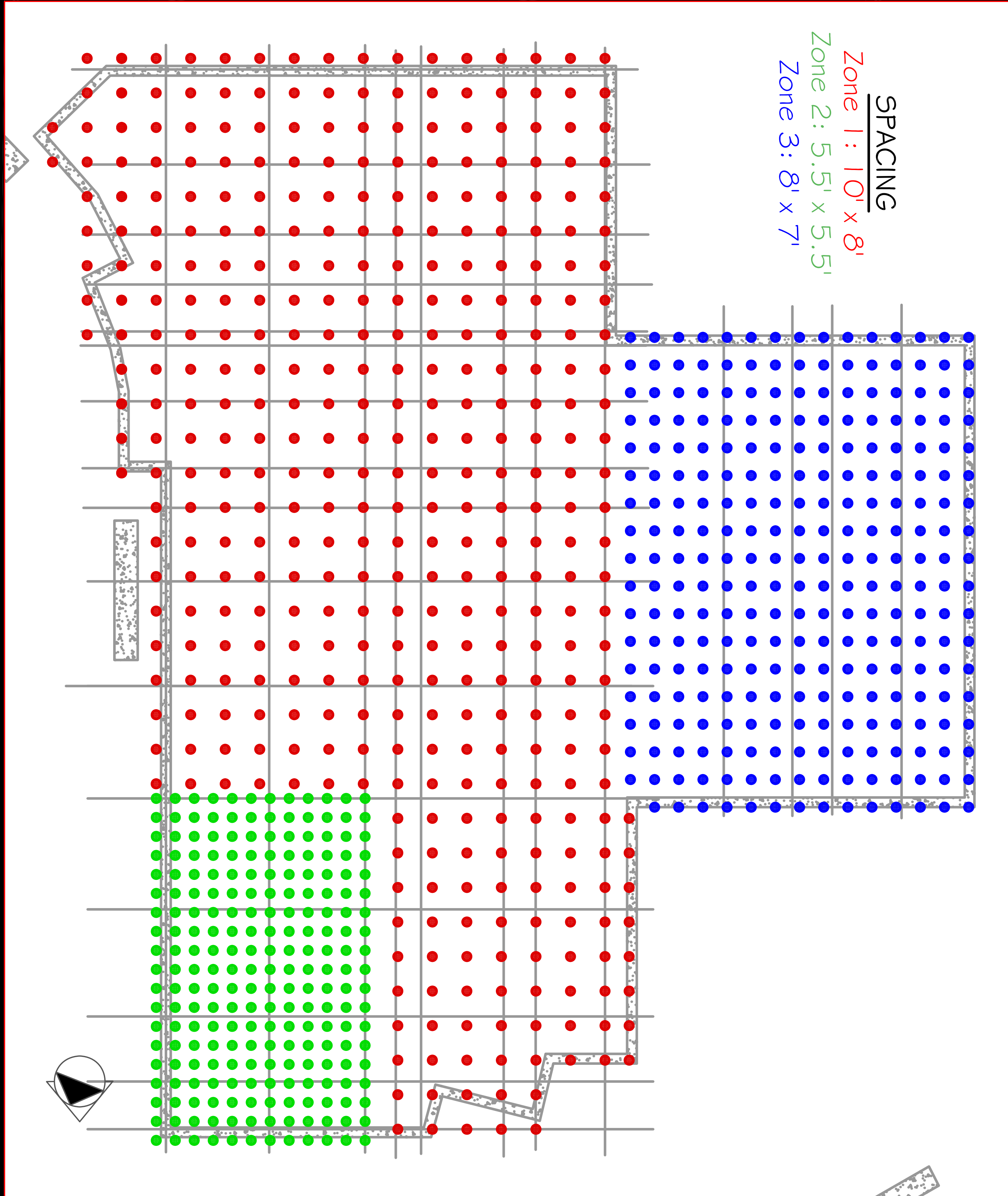
Totals for each zone's Geopier requirements are provided in Figure 4 below. The next two pages depict the pile layout plan versus the proposed Geopier grid. Design of the Geopier soil stabilization method follows the manual provided by GeoStructures, Incorporated, courtesy of CMT Labs. For full calculations, see Appendix A1.

Figure 4. Geopier Specifications

Zone	Footprint Size (SF)	Total Geopiers (30" dia., 15' Deep)	Nominal Spacing
1. Primary Area	36,733	419	10' x 8' O.C.
2. Radiotherapy Vaults	6,000	228	5'-6" x 5'-6" O.C.
3. Shell Space	13,811	269	8' x 7' O.C.

MICROPILE COORDINATION PLAN
(Courtesy of Coastal Drilling, East & Gilbane Building Company)





NO SCALE	FOUNDATION PLAN PROPOSED GEOPIER GRID	PSHMC CANCER INSTITUTE	PENNSTATE Milton S. Hershey Medical Center College of Medicine Gilbane

Mat Slab Calculation Results

An analysis of a mat slab-only foundation was performed for comparative analysis. Load distributions were again assumed to be uniform for each zone. Due to the lack of specific point load values, calculations were extrapolated from pile design capacities. While the Primary Area looks at a typical bay, the other spaces take into account the entire space because no columns are present or listed. Full results are found in Appendix A4.

Figure 5. Mat Slab Specifications

Zone	Footprint Size (SF)	Mat Slab Thickness Required
1. Primary Area	36,733	2'-9"
2. Radiotherapy Vaults	6,000	4'-6"
3. Shell Space	13,811	15"

Construction Analysis

The following section outlines critical construction issues associated with the proposed and existing foundation systems. Considering the scope of the redesign, it is necessary to perform a comprehensive review on its impact to all critical areas of construction management. Thus, the analysis is broken down into three core aspects- constructability and cost, scheduling and sequencing, and value engineering impacts.

Constructability Review

The most important consideration in this redesign is its cost implications to the project. Constructability of the two systems can be broken down into two categories:

- Micropiles versus Geopier Rammed Aggregate Piers
- Pile Caps, Grade Beams, & Slab on Grade versus Mat Slab

Analysis on each of these four categories is further broken down into material, equipment, and labor costs as defined by the trade contractors and vendors. Information not available from these sources is based on R.S. Means CostWorks software and prevailing wage data. The following costs are summarized from Appendix A6:

Figure 6. Summary Cost Comparison

Category	Cost		Category	Cost
Piles	$1,250,000	VS.	Geopiers	$618,300
Slab on Grade & Pile Caps	$941,552.82		Mat Slab	$2,079,756.50
Total Cost	**$2,191,552.82**		**Total Cost**	**$2,698,056.50**

Proposed System, Cost Addition = $506,504 (+ 23.1%)

As seen above, the proposed Geopier-reinforced mat slab foundation costs 23% more than the existing system. The bulk of the added costs come as a result of the mat slab pour. Though the mat slab calculations are basic from a structural standpoint, overall it was designed conservatively and may in reality be cheaper than these estimates. Also of importance is the fact that the Geopier estimate does not take into account savings accrued from using recycled aggregate, a potential alternative that benefits the Cancer Institute with respect to LEED points.

Piles versus Geopiers

The pile installation process is far more labor intensive than RAPs. The Cancer Institute will utilize 387 auger-placed piles comprised of (2) #18 Grade 75 bars encased in 7" pipe and filled with 4.5 ksi grout. One threaded bar extends the full length of the pile; the second extends only 5' above the 11' deep rock socket. Dependent upon the soil composition, drilling can proceed very slowly and incur difficulties with the casing bending or breaking, bearing piles deflecting out of vertical, and drill heads malfunctioning. Also of importance is the fact that mobilization and equipment costs can be very expensive. The Cancer Institute project will require support items

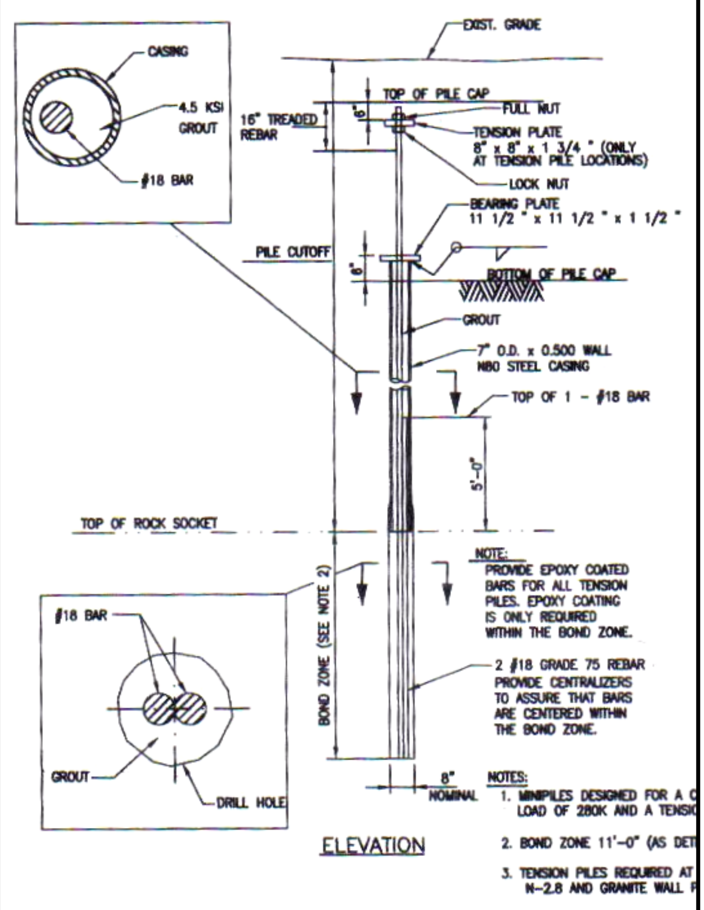
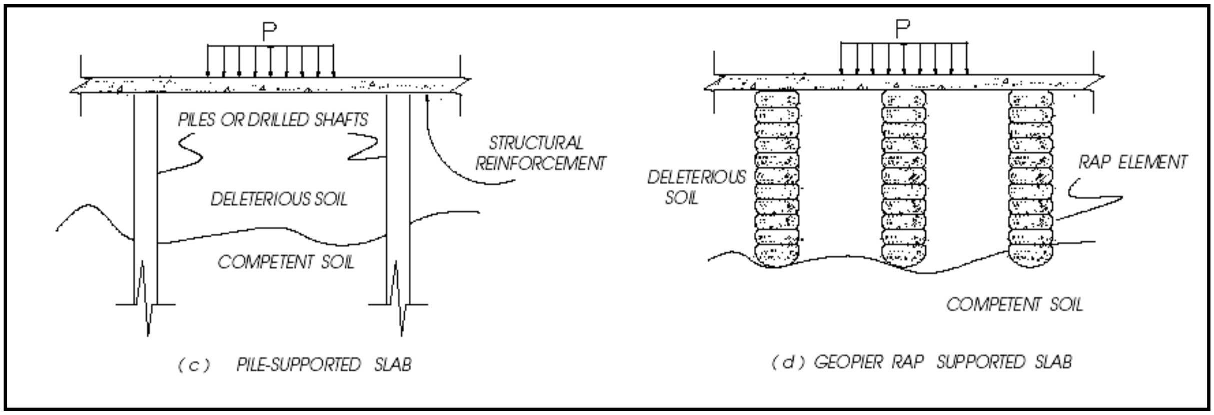


Figure 7. Micropile Detail

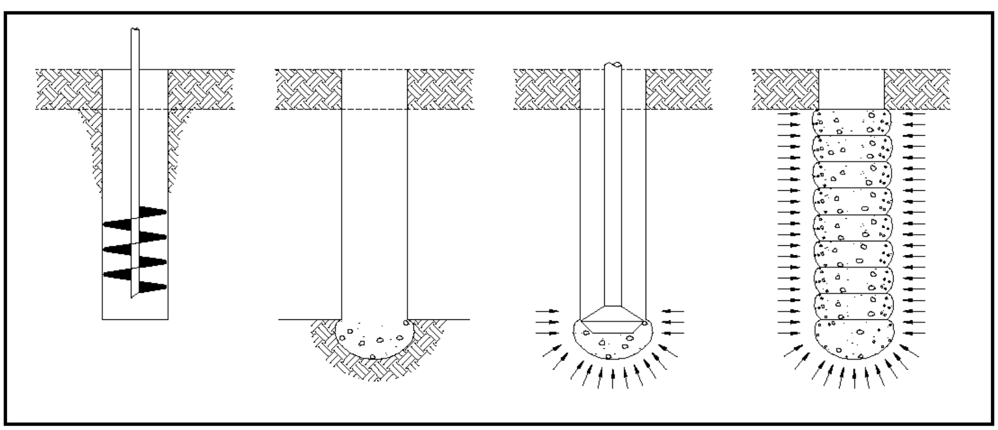
such as a cement silo, three hydraulic rigs, two forklifts, pumps and diesel compressors.

Figure 8. Pile-supported vs. RAP-supported Slab



The Geopier system, on the other hand, is significantly cheaper than the piles because they have been designed to extend only 10' feet into the ground and require fewer equipment and materials. Shallower, auger shafts also minimizes equipment sizing and strain on the subsurface soils. The proposed 30" RAPs need only #57, 3" washed aggregate for the bottom bulb and PennDOT 2A crushed stone for the remainder of the column. Not only does this free up space in terms of site logistics, but the process is simple from conception to installation (see Figure 9). It begins by making a cavity and placing the first lift of stone in the bottom. A beveled tampering rod then compacts the stone, with subsequent thin lifts placed atop one another.

Figure 9. Geopier Installation Schematic



Slab on Grade versus Mat Slab

Constructing the mat slab will be considerably more difficult than the existing slab on grade due to the extensive amount of rebar and embed placement. It is important to monitor the utility layouts closely so that slab penetrations are placed correctly through the thick slab. Whereas the current slab on grade ranges from 5” to 6” (excluding the Radiotherapy Vaults), the mat slab ranges from 15” to 33”, which will be placed atop an 8” stone layer similar to the SOG.

Schedule and Sequencing Implications

The proposed system creates a major impact on the schedule and sequencing of the project. Though there are nearly three times as many Geopiers than piles, and despite the more labor-intensive mat slab pour, a significant tradeoff comes into play when considering production rates. Whereas a team of three drilling crews are scheduled to average about 6 piles a day at the Cancer Institute, a crew of only five Geopier installers will average 33 piles in the same time span. Thus, the estimated 1600 rock columns can be completed in 28 days, 45% faster than the 62 day-schedule for installing the piles. In the overall structural sequence, however, this is only a fraction of the information that requires analysis.

Sequencing Impact

Currently the slab on grade is scheduled to be poured in two phases. Phase 1 consists of pouring Zone 1 only, which is the radiotherapy enclosure. The steel superstructure will then be installed, with Phase 2 of the pour starting when the steel tops out. This sequence, however, must change for the proposed mat slab foundation due to the fact that the steel needs the load-bearing slab beneath it.

With the new system, underslab utilities are an important issue to consider. Since the grid pattern of the RAPs is relatively dense, utility installation will have to precede this activity.

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The following tables summarize the sequencing and duration of pertinent structural activities planned for the existing and proposed systems, respectively. A detailed CPM schedule comparison follows on the next page:

Figure 10. Schedule Comparison Summary

Micropile and SOG Installation		
Activity	**Start – Completion Dates**	**Duration (days)**
Install & Grout Piles	12/12/06 to 3/8/07	62
Pour Pile Caps and Column Piers	2/2 to 3/29	40
Pour Radiotherapy Vaults	2/2 to 4/26	60
Install Underslab Utilities / Pour Fdn. Walls	3/30 to 4/26	20
Erect Steel (All Floors)	4/27 to 8/13	91
Pour Remaining Slab on Grade	7/31 to 8/13	10
Total Duration	**12/12/06 to 8/13/07**	**190 days**

Geopier RAP and Mat Slab Installation		
Activity	**Start – Completion Dates**	**Duration (days)**
Install Underslab Utilities	12/12/06 to 1/9/07	20
Install Geopiers	1/9 to 2/15	28
Pour Mat Slab & Fdn. Walls	1/22 to 3/30	48
Erect Steel (All Floors)	4/2 to 7/23	91
Total Duration	**12/12/06 to 7/23/07**	**175 days**

It is evident that the proposed foundation reduces the construction schedule considerably when two crews are sequenced on the mat slab installation, enabling elevated slabs to be poured a full 15 working days ahead of the existing schedule. Assuming that all other activities take the same amount of time, there are two key schedule impacts that need consideration.

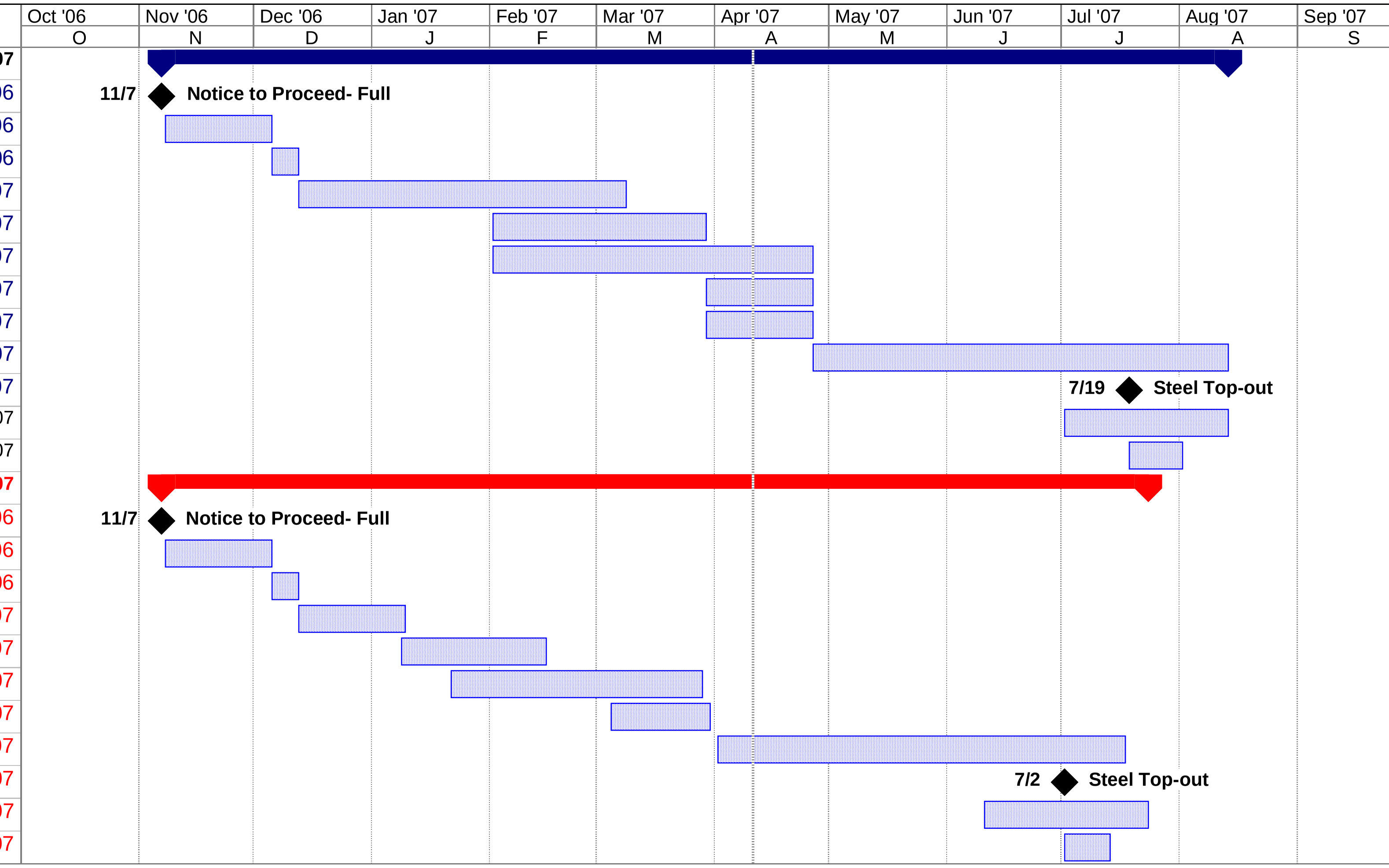
Slab Pour

A downside to the proposed system is the increased duration for the mat slab installation. However, rather than pouring the slab in phases, this process is streamlined into one activity and sequenced to follow the work of the Geopier contractors. In this scenario, the mat slab starts at about 50% completion of the Geopier elements to minimize congestion on the site. Thus, concrete placement starts on 1/22 and finishes 48 days later on 3/30. The schedule comparison ends up favoring the new system due to this more fluid construction sequence.

Penn State Milton S. Hershey Medical Center

Cancer Institute Project
Foundation Schedule Comparison

ID		Task Name	Duration	Start	Finish
1		**EXISTING FOUNDATION SYSTEM- MICROPILES & SOG**	**200 days**	**Tue 11/7/06**	**Mon 8/13/07**
2		Notice to Proceed- Full	0 days	Tue 11/7/06	Tue 11/7/06
3		Bulk Excavation	20 days	Wed 11/8/06	Tue 12/5/06
4		Sheeting and Shoring	5 days	Wed 12/6/06	Tue 12/12/06
5		Install Piles	62 days	Wed 12/13/06	Thu 3/8/07
6		Install Pile Caps/ Foundations	40 days	Fri 2/2/07	Thu 3/29/07
7		Pour Linac Enclosures	60 days	Fri 2/2/07	Thu 4/26/07
8		Install Foundation Walls	20 days	Fri 3/30/07	Thu 4/26/07
9		Install Underslab Utilities	20 days	Fri 3/30/07	Thu 4/26/07
10		Erect/ Trim Steel & Metal Decking (All Floors)	77 days	Fri 4/27/07	Mon 8/13/07
11		Steel Top-out	0 days	Thu 7/19/07	Thu 7/19/07
12		Rack and Trim Steel	31 days	Mon 7/2/07	Mon 8/13/07
13		Prep/ Pour Level 1	10 days	Thu 7/19/07	Wed 8/1/07
14		**PROPOSED FOUNDATION SYSTEM- GEOPIERS & MAT SLAB**	**185 days**	**Tue 11/7/06**	**Mon 7/23/07**
15		Notice to Proceed- Full	0 days	Tue 11/7/06	Tue 11/7/06
16		Bulk Excavation	20 days	Wed 11/8/06	Tue 12/5/06
17		Sheeting and Shoring	5 days	Wed 12/6/06	Tue 12/12/06
18		Install Underslab Utilities	20 days	Wed 12/13/06	Tue 1/9/07
19		Install Geopier RAPs	28 days	Tue 1/9/07	Thu 2/15/07
20		FRP Mat Slab & Linac Enclosures	48 days	Mon 1/22/07	Wed 3/28/07
21		Install Foundation Walls	20 days	Mon 3/5/07	Fri 3/30/07
22		Erect/ Trim Steel & Metal Decking (All Floors)	77 days	Mon 4/2/07	Tue 7/17/07
23		Steel Top-out	0 days	Mon 7/2/07	Mon 7/2/07
24		Rack and Trim Steel	31 days	Mon 6/11/07	Mon 7/23/07
25		Prep/ Pour Level 1	10 days	Mon 7/2/07	Fri 7/13/07



Project: PSHMC Cancer Institute
Date: 10/26/06

Task	Milestone	Rolled Up Task	Rolled Up Progress	External Tasks	Group By Summary
Progress	Summary	Rolled Up Milestone	Split	Project Summary	Deadline

Further, complications encountered by the RAP process require much less evaluation than a bad pile. One issue that arises with Geopiers is soil collapse during the compaction process. As long as the aggregate-to-soil ratio within the column remains at 90%, the Geopier is considered structurally sound and does not require re-excavation. Issues with individual micropiles, however, have much more damaging potential, as shown at the Parking Garage project. Revisiting that situation, the micropile duration ended up taking 50% longer than planned. If the Cancer Institute experiences a subsurface situation of the same magnitude, the project would be delayed 31 days.

Value Engineering Considerations

Aside from the benefits realized in the cost and schedule analyses, the proposed foundation system adds value to the Cancer Institute in terms of predictability, stability, and environmental impact. It is in these areas that PSHMC should be particularly interested, being both the owners and operators of this high-end facility.

Avoid Subsurface Problems

The proposed Geopier-reinforced mat slab system has inherent qualities that rival the existing deep micropile foundation. Though the cost savings are not there, it is important to recollect why the system was proposed in the first place- to avoid issues associated with placing deep, end-bearing elements into unreliable soils. The change order that occurred on the Parking Garage project may be dwarfed by potential problems at the Cancer Institute. If a similar fault line is found at a critical area of the foundation, such as the radiotherapy enclosure, redesign costs will be immense. This zone contains a 70-pile grid with piles placed 5'-6" on center

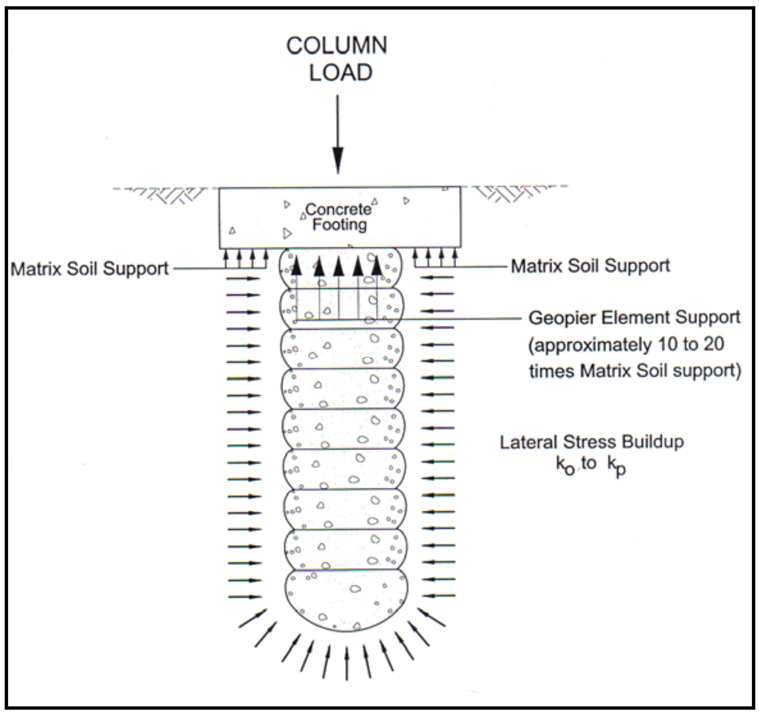


Figure 11. Soil Stabilization Effect of RAPs

placed 5’-6” on center in each direction. Competent rock issues with one pile in the grid will impact the entire layout as differential settlement must be accounted for. The sensitivity of the equipment above demands strict adherence to these tolerances.

Maintain Settlement Tolerances

Aside from the avoidance of any serious subsurface issues, there is also reassurance that the settlement of the mat slab will be contained well within tolerances due to the effectiveness of the Geopier soil stabilizers. Lateral pressures provided by the matrix of stone columns will even have a positive impact on soils of the adjoining Children’s Hospital. Though initial settlement calculations of the Geopier system exceeded typical tolerances of 1”, case studies of Geopier applications in the real world show that settlement is far less than the expected values. Monitoring the actual versus expected settlement of these systems is possible through the installation of electronic sensors in the slab and would be recommended for the Cancer Institute project. If in fact settlement is less than 1”, it would be a good argument for using Geopiers at the Children’s Hospital project as well.

ICRA Impact

Lastly, it is important to consider the impact of each system’s installation process on the daily hospital operations. The micropile installation process creates a serious issue when considering the sensitivity of the Emergency Delivery area to outside air contamination. During the drilling process, displacement of subsurface water forces excess amounts to the surface. This poses an infiltration threat to critical spaces nearby, most notably the Emergency Delivery area, Operating Rooms, and Dialysis Center. PSHMC has categorized these, and several other spaces, as High or Highest Risk areas in their comprehensive Infection Control Risk Assessment plan. In order to avoid contaminates from entering the hospital, many steps are being taken to ensure that all exterior penetrations are covered and negative pressure is maintained from within. Geopiers reduce the potential for airborne contamination by avoiding the water table completely and thus eliminating dirty water particles from the air.

This is not to say that RAPs don't present a contamination threat of their own; the ramming compaction technique sends finite stone particles into the air that can travel to the ICRA-protected spaces. The difference lies in the fact that Geopier installation can proceed during the day, whereas the piles are scheduled for nighttime placement. Vibrations and noise of the Geopier installation is considerably less than what is produced during the pile-drilling process.

Recommendation

Considering the significant added costs with the proposed system, it is difficult to recommend its implementation without a more thorough analysis of the exact mat slab specifications. However, when recalling the issues at the Parking Garage, there still lies potential for a damaging change order to the Cancer Institute foundation system. If this occurs, PSHMC and Gilbane should consider the Geopier-reinforced mat slab for the Children's Hospital project. The smaller footprint of this building will be more conducive to the mat slab alternative, which in the end benefits the project from a scheduling and sequencing perspective.