Shallow Foundations and Deep Foundations; Drilled Piers, Aggregate Piers and Stone Columns; Design Recommendations, Construction Considerations, and Performance

Hossein Alimohammadi, Ph.D., P.E. [1]

1- Terracon Consultants, Inc., Nashville, TN, USA 37217
Hossein.Alimohammadi@terracon.com

Abstract

This paper presents a comprehensive review of shallow foundations, floor slabs, and deep foundations, focusing on drilled piers, micropiles, aggregate piers, and stone columns. The study aims to consolidate definitions, design methodologies, and construction recommendations pertinent to these foundation types. Shallow foundations, including mat and spread footings, and floor slabs are reviewed with respect to their design considerations and construction techniques, emphasizing their role in efficiently supporting superstructures. Deep foundations such as drilled piers and micropiles are evaluated for their capacity to transfer loads to deeper, more stable layers of soil. The review includes discussions on their design principles, installation methods, and performance in different geotechnical contexts. Additionally, aggregate piers and stone columns are explored as ground improvement techniques, offering insights into their design parameters and construction practices to enhance soil bearing capacity and mitigate settlement issues. By synthesizing current literature and engineering practices, this review aims to provide engineers, researchers, and practitioners with a comprehensive resource for understanding the complexities of foundation design and construction. Key recommendations are offered to guide future research and practical applications in the field of geotechnical engineering.

Keywords: Shallow Foundations, Floor Slabs, Deep Foundations, Drilled Piers, Micropiles, Aggregate Piers, Stone Columns, Future Design and Construction

1- Shallow foundations definitions, design and construction recommendations

Shallow foundations, also known as footings, are a common type of foundation system used in construction. These foundations are employed where the bearing strata are close to the ground surface, and the loads imposed by the structure are relatively light. Shallow foundations are cost-effective and simpler to construct compared to deep foundations. The primary types of shallow foundations include strip footings, spread footings, mat or raft foundations, and combined footings. Each type has specific applications and design considerations. Shallow foundation systems are a vital component of construction, offering cost-effective and efficient solutions for a variety of structures. Understanding the different types of shallow foundations, their applications, and key design and construction considerations is essential for ensuring their successful implementation. Continued research and development in geotechnical engineering will further enhance the performance and reliability of shallow foundations in future construction projects.

Strip footings are continuous strips of concrete that support walls. They are commonly used in residential construction and low-rise buildings where the load distribution is linear. Strip footings are advantageous in terms of ease of construction and cost-efficiency, especially in cohesive soils where differential settlement is less of a concern. Spread footings, also known as isolated footings, support individual columns or piers. They are typically square or rectangular and distribute the load over a larger area to prevent excessive settlement. This type of footing is suitable for structures with relatively uniform load distributions and can be designed to accommodate varying soil conditions. Mat or raft foundations consist of a large slab of concrete that supports multiple columns and walls. These foundations are used when soil conditions are poor, and the load needs to be distributed over a wide area to reduce settlement. Mat foundations are common in high-rise buildings and structures with heavy loads, as they provide stability and uniform settlement characteristics. Combined footings support more than one column and are used when columns are close to each other, making individual footings impractical. They are designed to balance the load distribution and are typically employed in scenarios where the spacing between columns is too small for isolated footings.

Shallow foundations are utilized in a wide range of construction projects. Their applications span residential buildings, commercial structures, and light industrial buildings. Shallow foundations are extensively used in residential construction due to their simplicity and cost-effectiveness. Strip footings and spread footings are common choices for supporting walls and individual columns in houses and low-rise apartments. In commercial buildings, such as office buildings and shopping centers, mat foundations are often used to support the higher loads and ensure uniform settlement. Combined footings may also be employed to optimize space and load distribution in tightly spaced column layouts. Light industrial buildings, which may have varying load requirements and soil conditions, benefit from the versatility of shallow foundations. Spread footings and mat foundations are commonly used to support machinery, storage areas, and structural components.

The design of shallow foundations involves several critical considerations to ensure stability, durability, and performance under load. Understanding soil properties is fundamental in the design of shallow foundations. Soil bearing capacity, compressibility, and permeability influence the selection and design of the foundation type. Geotechnical investigations are essential to assess these properties and ensure the foundation can adequately support the imposed loads. Accurate load calculations are crucial for designing shallow foundations. The load includes the weight of the structure, live loads, and environmental loads such as wind and seismic forces. The foundation must be designed to distribute these loads evenly to prevent excessive settlement and potential failure. Settlement is a critical factor in the performance of shallow foundations. Differential settlement can cause structural damage and must be minimized. Design strategies, such as increasing the foundation area or using reinforced concrete, help control settlement and ensure long-term stability. Proper construction practices are essential to the success of shallow foundations. This includes ensuring accurate excavation, proper placement of reinforcement, and quality control of concrete. Adherence to design specifications and standards is crucial to avoid issues such as uneven settlement and structural failure.

The foundation settlement will depend upon the variations within the subsurface soil profile, the structural loading conditions, the embedment depth of the footings, the thickness of the compacted fill, and the quality of the earthwork operations. It should be noted that the sides of the excavation for spread footings must be nearly vertical, and the concrete should be placed neat against these vertical faces for the passive earth pressure value to be valid. If the loaded side is sloped or benched and then backfilled, the allowable passive pressure will be significantly reduced. It is recommended that the passive resistance in the upper 2 feet of the soil profile should be neglected. Lateral resistance due to friction at the base of the footing should be ignored where uplift also occurs. For bedrock-supported foundations, a probe hole for scratch testing of the bedrock should be performed by the contractor at the bottom of the footing for the Geotechnical Engineer’s use. The hole should be a minimum of 2 inches in diameter and extend to a depth equal to at least two times the foundation width but not less than 6 feet. The contractor should provide safe entry for the inspection, including air monitoring. Use of passive earth pressures requires the sides of the excavation for the spread footing foundation to be nearly vertical and the concrete placed neat against these vertical faces or that the footing forms be removed and compacted structural fill be placed against the vertical footing face. Embedment is necessary to minimize the effects of frost and/or seasonal water content variations. For sloping ground, maintain depth below the lowest adjacent exterior grade within 5 horizontal feet of the structure. Differential settlements are noted for equivalent-loaded foundations and bearing elevation as measured over a span of 50 feet. For bedrock-supported foundations, a probe hole for scratch testing of the bedrock should be installed by the contractor at the bottom of the footing for the Geotechnical Engineer’s use. The hole should be a minimum of 2 inches in diameter and extend to a depth equal to at least two times the foundation width and not less than 6 feet. The contractor should provide safe entry for the inspection, including air monitoring.

Shallow foundations subjected to overturning loads should be proportioned such that the resultant eccentricity is maintained in the center third of the foundation (e.g., $e < b/6$, where b is the foundation width). This requirement is intended to keep the entire foundation area in compression during the extreme lateral/overturning load event. Foundation oversizing may be required to satisfy this condition. Uplift resistance of spread footings can be developed from the effective weight of the footing and the overlying soils with consideration to the IBC basic load combinations and recommendations illustrated in Table 1.

Table 1. Uplift resistance of spread footings recommendations

Item	Description
Soil Moist Unit Weight	100 pcf
Soil Effective Unit Weight[1]	40 pcf
Soil weight included in uplift resistance	Soil included within the prism extending up from the top perimeter of the footing at an angle of 20 degrees from vertical to ground surface

1. Effective (or buoyant) unit weight should be used for soil above the foundation level and below a water level. The high groundwater level should be used in uplift design as applicable.

Similar construction consisting of bedrock-supported foundations has utilized rock anchors as a feasible and cost-effective option to resist uplift forces both in footings and crane pads. Prior to any rock anchor and foundation construction, the base of all foundation excavations should be essentially horizontal and free of water, soil, and loose or detached rocks before placing concrete. In addition, rock surfaces beneath foundations that are exposed after overburden removal and that are to be filled with lean concrete should be horizontal. Lateral and uplift loads can also be resisted using rock anchors. If foundations are designed with rock anchors, they should be installed in relatively intact bedrock with no clayey seams and weathered rock lenses. Intact bedrock for the purposes of this report is any rock that cannot be excavated with a large-size trackhoe or other heavy-duty excavator having REC/RQD values at least 90/75 or better. Rock anchors should extend into competent bedrock to provide ample resisting forces for upward movements and to obtain adequate bond length with the grout and rock, and grout and anchor rod. Uplift capacity of individual rock anchors should be calculated based on the weight of a cone of rock as shown in the adjacent diagram. Additional resistance will be provided by the friction across the fractures, which can be taken as an angle (ϕ) equal to 45 degrees. The apex of the cone should be placed from 0 to 1/4 of the way up from the bottom tip, depending on the anchor type. It is recommended that a unit weight (γ) of 150 pounds per cubic foot (pcf) be used for intact bedrock. An allowable bond strength of 200 pounds per square inch (psi) should be adequate for the limestone-grout interface when 3,000 psi strength grout is used. A factor of safety of 2.0 has been used for calculating the allowable grout-rock bond strength. Bond strength between the grout and anchor will be dependent on the anchor type and grout strength. It is recommended that the structural engineer and/or rock anchor designers determine rock anchor embedment to address potential failure modes (i.e., rock mass, grout/rock, and grout/rebar), but will require additional input from the design team. Based on the weathered and fractured condition of the anticipated bearing rock, it is recommended that a cone failure test setup be applied to the proof test as illustrated in Figure 1.

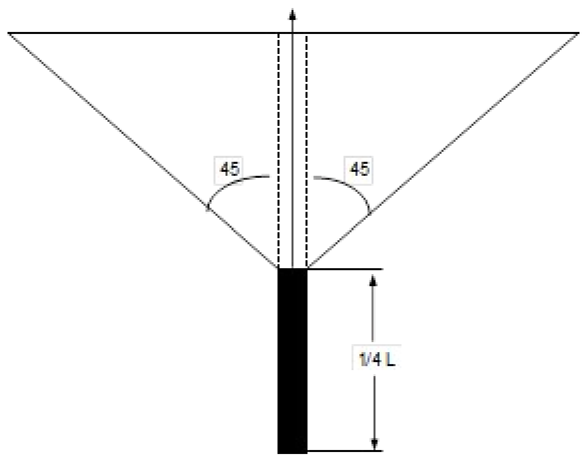


Figure 1. The cone failure test

When developing the appropriate tests and verification methods for construction, designers and contractors should review both FHWA-IF-99-015 and ASTM D3689-07 (Reapproved 2013) for testing apparatuses, setups, and loading guidelines. Given the REC and RQD values of the bedrock, it is suggested that only the bond of the anchor to the bedrock requires testing, not the bedrock failure cone. At a minimum, a proof load test should be conducted on each anchor installed. For proof testing, the anchor is initially loaded with a seating load of 10 percent of the design load. Subsequently, the anchor is stressed in increments of 25 percent of the design load with elongation measurements recorded at each increment. Proof loading is applied in sequential increments in one cycle and is generally carried to 125 percent of the design load. A reasonable period of time is allowed between load increments so that the anchor elongation has stabilized before starting the next load increment. The maximum proof load is held for a period of between 5 minutes and one hour. In no case should an anchor be loaded to more than 80 percent of the ultimate tensile capacity of the steel tendon.

Uplift resistance of spread footings can be developed from the effective weight of the footing and the overlying soils. As illustrated in Figure 2, the effective weight of the soil prism defined by diagonal planes extending up from the top of the perimeter of the foundation to the ground surface at an angle, θ, of 20 degrees from the vertical can be included in uplift resistance. The maximum allowable uplift capacity should be taken as the sum of the effective weight of soil plus the dead weight of the foundation, divided by an appropriate factor of safety. A maximum total unit weight of 100 pcf should be used for the backfill. This unit weight should be reduced to 40 pcf for portions of the backfill or natural soils below the groundwater elevation.

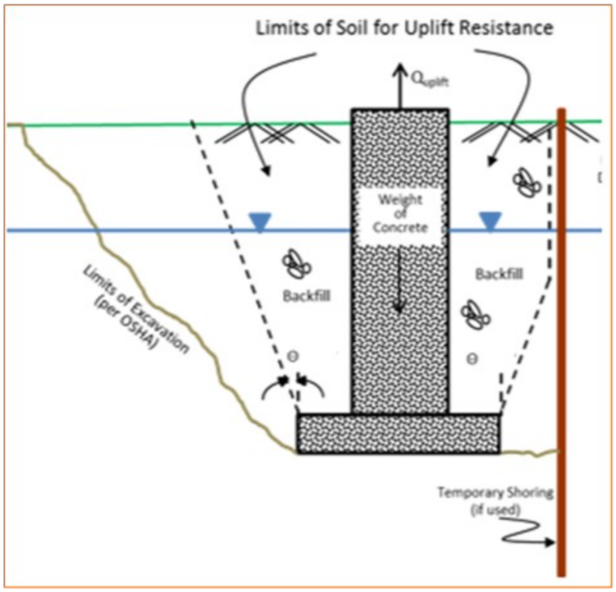


Figure 2. The diagonal planes extending up from the top of the perimeter of the foundation to the ground surface

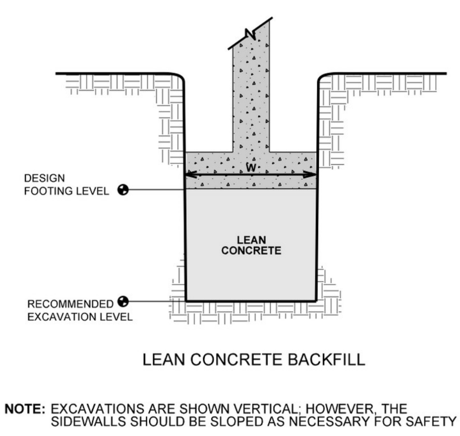
To ensure the successful implementation of shallow foundations, the following construction recommendations should be considered: Proper site preparation is vital. This includes clearing the site of debris, ensuring a level base, and compacting the soil to the required density. Any unsuitable soil should be removed and replaced with appropriate fill material. Excavation must be carried out according to design specifications. The depth and dimensions of the excavation should match the foundation plans. Shoring or bracing may be necessary in loose or unstable soils to prevent collapse during excavation. Placing reinforcement accurately is essential for the structural integrity of the foundation. Reinforcement should be positioned according to the design drawings, with proper spacing and cover to protect against corrosion and ensure load transfer. The quality of concrete and proper curing practices significantly impact the foundation's performance. Concrete should be mixed to the specified strength and poured without interruptions. Adequate curing methods, such as keeping the concrete moist, are necessary to achieve the desired strength and durability. Implementing a robust quality control process ensures that the foundation construction meets the design standards. Regular inspections, material testing, and adherence to construction protocols help identify and rectify issues promptly.

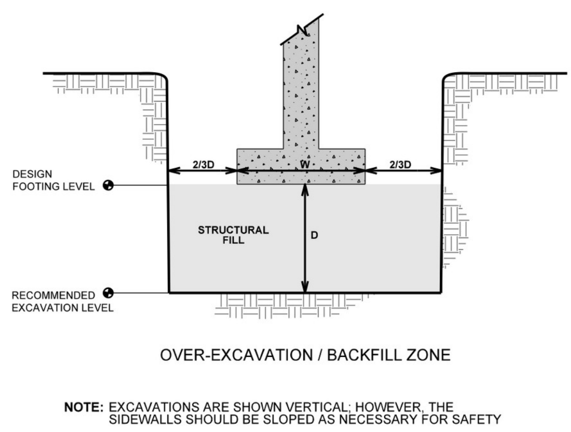
The footing excavations should be evaluated under the observation of the Geotechnical Engineer. The base of all foundation excavations should be free of water and loose soil/rock prior to placing concrete. Concrete should be placed soon after excavating to reduce bearing soil disturbance. Care should be taken to prevent wetting or drying of the bearing materials during construction. Excessively wet or dry material or any loose/disturbed material in the bottom of the footing excavations should be removed or reconditioned before foundation concrete is placed.

If the expected cuts for the lowest level of the structure and where the site's perimeter and cuts transition will likely result in some foundations bearing on weathered bedrock or other softer-than-rock materials, then this will result in different bearing materials over a short distance. Experience indicates that this condition could result in differential settlement and cracking within masonry walls where the material transition occurs or between ancillary and main structure foundations. To minimize this condition, it is recommended that where weathered or unsuitable bedrock is exposed in isolated areas, overexcavate the bedrock to competent bedrock and backfill with lean concrete, or bear the entire wall length between expansion joints on similar materials, either rock or suitable structural fills.

Since it is impractical to determine exactly where this condition will occur within the structures, adjustments will have to be performed in the field under the direction of the geotechnical engineer. A liberal number of expansion joints should be incorporated into the structure design to accommodate differential movement.

If unsuitable bearing soils are observed at the base of the planned footing excavation, the excavation should be extended deeper to suitable soils, and the footings could bear directly on these soils at the lower level or on lean concrete backfill placed in the excavations. The lean concrete replacement zone is illustrated in the sketch in Figure 3.





a) **b)**

Figure 3. a) and b) Overexcavation for structural fill placement

Overexcavation for structural fill placement below footings should be conducted as shown below. The overexcavation should be backfilled up to the footing base elevation, with well graded aggregates placed. Experience has indicated that rock formations which can be penetrated with geotechnical drill flight augers can sometimes be excavated using heavy-duty construction equipment such as large backhoes with rock teeth or ripper-equipped dozers. Excavation in rock formations which cannot be penetrated with geotechnical drill flight augers is usually much more difficult and often requires the use of other techniques such as pneumatic breakers or blasting. The contractors should anticipate and plan that excavations will extend into bedrock. Rippability of the bedrock will vary, and the use of jackhammers and other rock excavation equipment and/or methods is anticipated to be required to reach the anticipated excavation depths. Furthermore, if blasting methods are used that may disturb the bedrock below the desired depth, then any loosened bedrock pieces should be recompacted as outlined for “shot rock” fill, or removed and replaced with suitable engineered fill or lean concrete. Heaved or dislodged fragments of bedrock should not remain in place as they pose a risk for unpredictable settlement and potential void collapse.

2- Floor slab definitions, design and construction recommendations

Floor slabs are crucial structural elements in building construction, serving as horizontal platforms that transfer loads to supporting structures. They are primarily categorized into solid, hollow-core, ribbed, and waffle slabs. Solid slabs are often employed in residential and commercial buildings due to their simplicity and ease of construction. Hollow-core slabs, characterized by longitudinal voids, are used in multi-story buildings for their efficiency in material usage and weight reduction. Applications of floor slabs extend to various structures, including residential, commercial, and industrial buildings, each demanding specific design considerations. In high-rise buildings, post-tensioned slabs are preferred for their enhanced load-bearing capacity and reduced deflection. In industrial settings, reinforced concrete slabs are chosen for their durability and ability to withstand heavy loads.

Design recommendations emphasize the importance of load calculations, material selection, and adherence to building codes. Modern design approaches incorporate finite element analysis (FEA) to accurately predict slab behavior under various loading conditions. Construction recommendations stress proper curing, reinforcement placement, and quality control to ensure structural integrity and longevity. Design parameters for floor slabs are provided in Table 2. Specific attention should be given to positive drainage away from the structures and the positive drainage of the aggregate base beneath the floor slab.

Table 2. Floor slab design parameters

Item	Description
Floor Slab Support [1]	Minimum 6 inches of free-draining (less than 5% passing the U.S. No. 200 sieve) crushed aggregate compacted to at least 95% of ASTM D 698 or #57 stone [2, 3]
Estimated Modulus of Subgrade Reaction [2]	100 pounds per square inch per inch (psi/in) for point loads

1. Floor slabs should be structurally independent of building footings or walls to reduce the possibility of floor slab cracking caused by differential movements between the slab and foundation.
2. Modulus of subgrade reaction is an estimated value based upon our experience with the subgrade condition, and the floor slab support as noted in this table. It is provided for point loads. For large area loads the modulus of subgrade reaction would be lower.
3. Free-draining granular material should have less than 5% fines (material passing the No. 200 sieve). Other design considerations such as cold temperatures and condensation development could warrant more extensive design provisions.

Advancements in construction technologies, such as precast and prefabricated slabs, have streamlined the construction process, reducing time and labor costs. Sustainable practices, including the use of recycled materials and energy-efficient designs, are increasingly integrated into floor slab construction, aligning with global trends toward environmentally responsible building practices.

The use of a vapor retarder should be considered beneath concrete slabs on grade covered with wood, tile, carpet, or other moisture-sensitive or impervious coverings, or when the slab will support equipment sensitive to moisture. When conditions warrant the use of a vapor retarder, the slab designer should refer to ACI 302 and/or ACI 360 for procedures and cautions regarding the use and placement of a vapor retarder.

Saw-cut control joints should be placed in the slab to help control the location and extent of cracking. For additional recommendations, refer to the ACI Design Manual. Joints or cracks should be sealed with a waterproof, non-extruding compressible compound specifically recommended for heavy-duty concrete pavement and wet environments.

Where floor slabs are tied to perimeter walls or turn-down slabs to meet structural or other construction objectives, our experience indicates differential movement between the walls and slabs will likely be observed in adjacent slab expansion joints or floor slab cracks beyond the length of the structural dowels. The Structural Engineer should account for potential differential settlement through the use of sufficient control joints, appropriate reinforcing, or other means. In addition to the mitigation measures, the floor slab can be stiffened by adding steel reinforcement, grade beams, and/or post-tensioned elements.

Regarding floor slab construction considerations, finished subgrade within and for at least 10 feet beyond the floor slabs should be protected from traffic, rutting, or other disturbances and maintained in a relatively moist condition until floor slabs are constructed. If the subgrade becomes damaged or desiccated before the construction of floor slabs, the affected material should be removed, and structural fill should be added to replace the resulting excavation. Final conditioning of the finished subgrade should be performed immediately before the placement of the floor slab support course.

The Geotechnical Engineer should approve the condition of the floor slab subgrades immediately before the placement of the floor slab support course, reinforcing steel, and concrete. Attention should be paid to high-traffic areas that were rutted and disturbed earlier, and to areas where backfilled trenches are located.

Before the construction of grade-supported slabs, varying levels of remediation may be required to reestablish stable subgrades within slab areas due to construction traffic, rainfall, disturbance, desiccation, etc. As a minimum, confirm that interior trench backfill placed beneath slabs is compacted in accordance with recommendations outlined in this report. All floor slab subgrade areas should be moisture-conditioned and properly compacted to the recommendations in this report immediately before the placement of the stone base and concrete.

3- Deep foundation including drilled piers and micropiles, aggregate piers and stone columns definitions, design and construction recommendations

Deep foundation systems are integral components in constructing structures where surface soils cannot support the load. This review covers three primary types of deep foundations: drilled piers and micropiles, aggregate piers, and stone columns. These systems offer various applications, advantages, and construction methods tailored to specific geotechnical conditions.

As an alternative to a shallow foundation support system, buildings should be supported on a deep foundation system (drilled piers or micropiles) extending to intact bedrock. When the building location is finalized and footing locations are precisely staked in the field by the surveyor, considerations should be given to perform air track probings at each footing location before construction. This will confirm the depth to intact bedrock, finalize pier or pile locations and depths, and ensure all piers or piles are embedded within intact bedrock below any voids and/or thick clayey seams encountered in borings. Additional borings are recommended to confirm boring data and the preliminary foundation recommendations outlined herein when the building location, structural loadings, and grading configuration are available.

The allowable skin friction and passive resistances have a factor of safety of about 2. To mobilize the rock strength parameters, the piers or piles should be socketed at least 3 feet into intact bedrock below any voids or thick clayey seams. Furthermore, it is assumed that the rock socket is developed using coring rather than blasting techniques. The upper 2 feet of clay should be ignored due to the potential effects of frost action and construction disturbance. To avoid a reduction in lateral and uplift resistance caused by variable subsurface conditions, it is recommended that drawings instruct the contractor to notify the engineer if subsurface conditions significantly different from those encountered in our borings are disclosed during drilled pier installation. Under these circumstances, it may be necessary to adjust the overall length of the piers. To facilitate pier length adjustments that may be necessary because of variable soil and rock conditions, it is recommended that a Geotech engineer representative observe the drilled pier excavations.

A drilled pier foundation should be designed with a minimum shaft diameter of 30 inches to facilitate cleanout, inspection, and possible dewatering of the pier excavation. Temporary casing will be required during the pier excavation to control possible groundwater seepage and support the sides of the excavation in weak soil or weathered rock zones. Care should be taken so that the sides and bottom of the excavations are not disturbed during construction. The bottom of the shaft should be free of soil or loose rocks before reinforcing steel and concrete placement.

A concrete slump of at least 6 inches is recommended to facilitate temporary casing removal. It should be possible to remove the casing from a pier excavation during concrete placement provided that the concrete inside the casing is maintained at a sufficient level to resist any earth and hydrostatic pressures outside the casing during the entire casing removal procedure. It is strongly recommended that the contract for pier excavations or micropile drilling be based on a total linear footage of soil and rock excavation calculated using probable bearing levels. Add or deduct unit prices for pier excavations or micropile drilling should be applied to greater or lesser amounts of total drilling per pier or pile rather than calculated on an individual pier or pile basis.

When shafts are used in groups, the lateral capacities of the shafts in the second, third, and subsequent rows of the group should be reduced compared to the capacity of a single, independent shaft. Guidance for applying p-multiplier factors to the p values in the p-y curves for each row of pier foundations within a pier group is illustrated in figure 4.

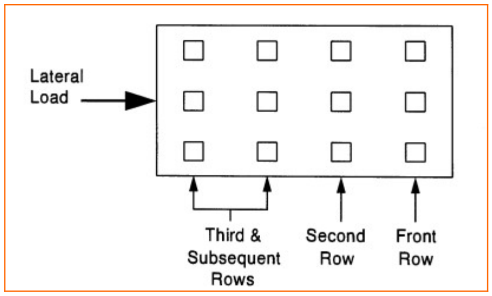


Figure 4. shafts used in groups

Where the Front row will be P_m is 0.8; Second row; P_m is 0.4,Third and subsequent row and P_m is 0.3. For a single row of shafts supporting a laterally loaded grade beam, group action for lateral resistance of shafts should be considered when spacing is less than three shaft diameters (measured center-to-center). However, spacing closer than 3D (where D is the diameter of the shaft) is not recommended, due to the potential for the installation of a new shaft disturbing an adjacent installed shaft, likely resulting in axial capacity reduction.

Regarding drilled shaft construction considerations, to prevent the collapse of the sidewalls and/or to control groundwater seepage, the use of temporary steel casing and/or slurry drilling procedures may be required for constructing the drilled shaft foundations. The drilled shaft installation process should be performed under the direction of the Geotechnical Engineer. The Geotechnical Engineer should document the shaft installation process, including soil/rock and groundwater conditions encountered, consistency with expected conditions, and details of the installed shaft. A concrete slump of at least 6 inches is recommended to facilitate temporary casing removal. It should be possible to remove the casing from a pier excavation during concrete placement provided that the concrete inside the casing is maintained at a sufficient level to resist any earth and hydrostatic pressures outside the casing during the entire casing removal procedure. Care should be taken not to disturb the sides and bottom of the excavation during construction. The bottom of the shaft excavation should be free of loose material before concrete placement. Concrete should be placed as soon as possible after the foundation excavation is completed to reduce potential disturbance of the bearing surface.

Aggregate piers, also known as vibro stone columns or vibro-replacement, are used to improve the load-bearing capacity of weak soils. They are particularly effective in granular soils and have been widely used in constructing embankments, industrial structures, and residential buildings (Mitchell & Huber, 2014). The design of aggregate piers involves determining the optimal spacing, diameter, and depth of the piers to achieve the desired soil improvement. The installation process increases the density and strength of the surrounding soil, leading to improved load distribution and reduced settlement (Greenwood, 2004). Design methodologies often rely on empirical data and field testing to validate assumptions. Construction of aggregate piers involves drilling a hole into the ground, followed by the introduction of aggregate material. The aggregate is then compacted using a vibrating probe, which helps to densify the soil and form a stiff column. This process may be repeated in lifts to ensure thorough compaction and soil improvement (Kempfert & Gebreselassie, 2006).

Based on our evaluation of the soil conditions encountered at the site and our experience on other similar projects, it is believed that aggregate piers (stone columns) offer an economical alternative to undercut/replacement and deep foundation options. To provide initial guidance, it is recommended that the structural engineer consult with one or more specialty contractors for further details. Additional information can be found in the U.S. Department of Transportation Federal Highway Administration, Publication No. FHWA-SA-98-086, Demonstration Project 116. General comments concerning this approach are provided in the subsequent paragraphs.

Aggregate piers are constructed by drilling a hole, removing a volume of soil, and then building a bottom bulb of clean, well-graded crushed aggregate while vertically pre-stressing and pre-straining subsoils underlying the bottom bulb. The aggregate pier shaft is built on top of the bottom bulb, using open-graded base course stone placed in thin lifts. The rammed aggregate pier elements are a proprietary subgrade reinforcing system and should be designed and constructed by an installer licensed by the ground improvement foundation company. The design parameters should be verified by a full-scale modulus test (similar to a pile load test) performed in the field. The Geotechnical Consultant should be retained to monitor the modulus test and subsequent production rammed aggregate pier installations.

The installer should provide detailed design calculations sealed by a professional engineer licensed in the State of Tennessee. The design calculations should demonstrate that the ground improvement method is estimated to control long-term settlements to less than 1-inch total and ½-inch differential, or a more stringent requirement if determined by the structural engineer. After the implementation of the above-mentioned ground improvement program and planned grading as discussed herein, the proposed building could be designed to rest on shallow footings overlying stone column modified subgrade. Shallow footings may be preliminarily designed for an allowable bearing pressure of 5,000 psf. This value should be confirmed by the stone column contractor/designer. The stone column specialty contractor should coordinate ground modification work including spacing of stone columns with the structural engineer to achieve the required bearing pressure and facilitate the spacing of control joints in the structure. Considering the apparent karst activity at the site, considerations should be given to the use of cement-treated aggregate for stone column construction to minimize surface water migration into the ground and mitigate karst risk.

The proposed building columns and walls could be designed to rest on shallow foundations after subgrade remediation via stone columns as discussed herein. Based on our evaluation of the soil conditions encountered and our experience with other similar projects, it is believed that stone columns offer an economical alternative to deep foundations. Ground improvement options may include aggregate piers using vibro-replacement techniques or rammed aggregate piers extending to suitable natural subgrade. It is recommended that this report and the appendices be provided to the ground improvement contractors/designers for pricing and subsequent design.

Stone columns are similar to aggregate piers but are typically used in cohesive soils to reduce settlement and increase load-bearing capacity. They are effective in improving ground conditions for a variety of structures, including roadways, railways, and industrial facilities (Baumann & Bauer, 1974). The design of stone columns involves assessing soil conditions and load requirements to determine the appropriate column spacing, diameter, and depth. Stone columns increase the shear strength of the soil and accelerate consolidation by providing drainage paths for pore water (Priebe, 1995). Design approaches often incorporate both analytical methods and field testing to ensure accuracy.

Stone columns are constructed using a vibratory probe to displace soil and introduce coarse aggregate material. The probe compacts the aggregate as it is inserted, forming a column that enhances the strength and stiffness of the surrounding soil. This method is particularly effective in reducing liquefaction potential in seismic regions (Barksdale & Bachus, 1983). When selecting and designing deep foundation systems, engineers must consider a variety of factors, including soil conditions, load requirements, environmental impact, and cost. Proper site investigation and soil testing are crucial for determining the most suitable foundation type and design parameters. Advanced modeling techniques and field testing can enhance the reliability and performance of these systems (Das, 2010). Quality control during construction is vital for the successful implementation of deep foundations. This includes monitoring drilling and installation processes, ensuring the correct placement of materials, and conducting post-construction testing to verify performance. Techniques such as load testing, cross-hole sonic logging, and pile integrity testing are commonly used to assess the quality of installed foundations (FHWA, 2006).

Conventional stone columns are constructed using a vibro-replacement or vibro-displacement method. A similar approach, consisting of rammed aggregate piers or Geopier® elements, involves removing a volume of soil and then building a bottom bulb of clean stone or aggregate. The Geopier shaft is built on top of the bottom bulb, using well-graded highway base course stone placed in thin lifts (12-inches compacted thickness). The lifts are compacted by a repeated ramming action that also stresses the soil laterally. Our preliminary design consideration indicates the rammed aggregate pier elements will be capable of supporting a net allowable bearing pressure of 5,000 psf. The recommended allowable bearing pressure is the pressure in excess of the minimum surrounding overburden pressure at the footing base elevation. This bearing pressure should be considered preliminary and should be confirmed by a stone column specialty contractor. An allowable passive resistance of 750 psf will be appropriate below the upper 2 feet of the soil profile. Passive resistance in the upper 2 feet of the soil profile should be neglected.

Current design methods are relatively empirical and based on field evaluations of a select number of projects. The foundation systems are proprietary and would be designed and installed by a specialty contractor. The installer should provide detailed design calculations sealed by a professional engineer licensed in the State of Tennessee. It is also recommended that specialty contractors should be contacted and given an opportunity to perform settlement analyses and confirm that settlements will be within the client's tolerable limits. The design calculations should demonstrate that stone column soil reinforcement will control long-term settlements to desired tolerable levels. The geotechnical engineer should be retained to monitor the field instrumentation and a contractor-executed load test program to evaluate the performance of the stone column design.

Drilled piers, also known as drilled shafts or caissons, are cylindrical foundation elements that transfer building loads to deeper, more stable soil or rock layers. They are typically used in large-scale infrastructure projects such as bridges, high-rise buildings, and industrial facilities where high load-bearing capacity and stability are required (Brown et al., 2010). The design of drilled piers involves careful consideration of soil properties, load requirements, and environmental factors. Key design parameters include the diameter and depth of the pier, the type of reinforcing steel used, and the concrete mix. Load-bearing capacity is typically determined through a combination of soil testing and empirical formulas (O'Neill & Reese, 1999). Construction of drilled piers involves drilling a cylindrical hole into the ground, placing a steel reinforcement cage, and then filling the hole with concrete. The use of temporary casing or drilling fluid may be necessary to support the excavation and prevent collapse in unstable soils (Reese & Van Impe, 2001). Quality control is critical during construction to ensure the integrity and performance of the piers.

Recent advancements in deep foundation technology include the use of high-performance materials, automated installation techniques, and improved monitoring systems. Innovations such as self-compacting concrete, real-time monitoring of installation parameters, and the integration of geotechnical data into building information modeling (BIM) are enhancing the efficiency and reliability of deep foundation systems (Ng et al., 2018).

4- Conclusions

In conclusion, this review paper has comprehensively explored various types of foundations crucial to civil engineering practice: shallow foundations, floor slabs, and deep foundations such as drilled piers, micropiles, aggregate piers, and stone columns. By examining definitions, design methodologies, and construction recommendations for each type, this study has highlighted their respective advantages, challenges, and suitable applications in diverse geotechnical contexts. Shallow foundations, including isolated footings and raft foundations, remain fundamental for structures where soil bearing capacity is sufficient near the surface. They offer cost-effective solutions for buildings and structures with moderate loads. Floor slabs, essential for residential and industrial constructions, require careful consideration of load distribution and material properties to ensure long-term performance and durability. Conversely, deep foundations like drilled piers, micropiles, aggregate piers, and stone columns are indispensable for transferring heavy structural loads to deeper, more competent soil or rock layers. Their design intricacies involve geotechnical analysis, structural compatibility, and construction techniques tailored to specific ground conditions. By synthesizing current knowledge and practices, this review contributes valuable insights into the complex interplay between foundation types, design principles, and construction methodologies. It underscores the importance of informed decision-making in selecting and implementing appropriate foundation systems to ensure the safety, stability, and longevity of civil engineering projects in varying environmental and geological settings. Future research should continue to refine and innovate these foundational technologies in response to evolving engineering challenges and sustainability imperatives.

Acknowledgments

The author would like to acknowledge the engineers in the Terracon company in Nashville, TN, and thank them for their help in providing the data for this research. The opinions, findings, and conclusions presented herein are those of the author and do not necessarily reflect any sponsors.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Brauns J (1978) Initial bearing capacity of stone columns and sand piles. Soil reinforcing and stabilizing techniques in engineering practice, Sydney I, pp 497–512

[2] Yahiaoui A., Dorbani S., Yahiaoui L., Machine learning techniques to predict the fundamental period of infilled reinforced concrete frame buildings, Structures, 10.1016/j.istruc.2023.05.052, 54, (918-927), (2023).

[3] Black JV, Sivakumar V, McKinley JD (2007) Performance of clay samples reinforced with vertical granular columns. Can Geotech J

44:89–95

[4] M. Abu-Farsakh, H. Alimohammadi, and L. N. Mohammad, “Finite Element Analysis to Evaluate the Benefits of Geosynthetic Reinforcement in Flexible Pavements Over Weak Subgrade for Low-Volume Traffic Roads,” Transp. Res. Board Conf. 99th Annu. Meet., 2020. https://annualmeeting.mytrb.org/OnlineProgramArchive/Details/12333

[5] H. Alimohammadi and B. Izadi Babokani, “Finite element electrodynamics modeling of a layered piezoelectric composite shell with different materials by using numerical software,” ISSS J. Micro Smart Syst., 2020.

[6] H. Alimohammadi, “A framework for evaluation of existing pavement conditions and selection of feasible maintenance/rehabilitation alternatives; a case study in some routes of Livingston Parish in the state of Louisiana,” SN Appl. Sci., vol. 2, no. 2, p. 289, Feb. 2020. https://doi.org/10.1007/s42452-020-1999-6

[7] G. Zheng, H. Alimohammadi, J. Zheng, and V. R. Schaefer, “Effectiveness of Geosynthetics in the Construction of Roadways: A Full-Scale Field Studies Review,” International Foundations Congress and Equipment Expo 2021, 2021, pp. 223–232. https://doi.org/10.1061/9780784483411.022

[8] H. Alimohammadi, V. R. Schaefer, J. Zheng, and H. Li, “Performance evaluation of geosynthetic reinforced flexible pavement: a review of full-scale field studies,” Int. J. Pavement Res. Technol., 2020. https://doi.org/10.1007/s42947-020-0019-y

[9] H. Alimohammadi, V. Schaefer, J. Ashlock, A. Buss, C. Rutherford, and B. Li, “Effectiveness of geogrids in roadway construction; determine a granular equivalent (G.E.) factor.”

[10] H. Alimohammadi, J. Zheng, A. Buss, V. R. Schaefer, C. Williams, and G. Zheng, “Field and simulated rutting behavior of hot mix and warm mix asphalt overlays,” Constr. Build. Mater., vol. 265, p. 120366, Dec. 2020. https://doi.org/10.1016/j.conbuildmat.2020.120366

[11] Bauman V, Bauer GE (1974) The performance of foundations on various soils stabilized by the vibro-compaction method. Can Geotech J 11(4):509–530

[12] H. Alimohammadi and · Jamal Tahat, “A case study experimental pile load testing (PLT) for evaluation of driven pile behaviors,” Arab. J. Geosci. 2022 159, vol. 15, no. 9, pp. 1–11, Apr. 2022. https://doi.org/10.1007/s12517-022-10176-5

[13] H. Alimohammadi and · Jamal Tahat, “A Case Study Pile Load Testing (PLT) to Evaluate Driven Pile Behaviors,” Indian Geotechnical Journal. Volume 52, pages 959–968, 2022. https://doi.org/10.1007/s40098-022-

00613-3

[14] H. Alimohammadi, M. Amirmojahedi, and J. N. Tahat, “A Case History of Application of Deep Compaction Method with Comparison to Different Ground Improvement Techniques,” Transp. Infrastruct. Geotechnol., pp. 1–26, Mar. 2022. https://doi.org/10.1007/s40515-022-00229-3

[15] S. Satvati, H. Alimohammadi, M. A. Rowshanzamir, and S. M. Hejazi, “Evaluation the Effects of Geosynthetic Reinforcement on Bearing Capacity of Shallow Foundations in Soil Slopes,” 101st Transp. Res. Board Annu. Meet., 2022. https://annualmeeting.mytrb.org/OnlineProgram/Details/17240

[16] H. Alimohammdi, V. R. Schaefer, J. Zheng, C. T. Jahren, G. Zheng, and D. White, “Effectiveness of Geotextiles/Geogrids in Roadway Construction; Determine a Granular Equivalent (GE) Factor,” Minnesota Dep. Transp., 2021. https://www.dot.state.mn.us/research/reports/2021/202126.pdf

[17] H. Alimohammadi, V. Schaefer, J. Zheng, D. J. White, and G. Zheng, “A State-of-the-art Large-scale Laboratory Approach to Evaluating the Effectiveness of Geogrid Reinforcement in Flexible Pavements,” Geosynthetics Conference 2021, 2021. https://osf.io/2d4gk/

[18] H. Alimohammadi, A. Buss, V. R. Schaefer, J. Zheng, and G. Z. Christopher Williams, “Finite element viscoelastic simulations of rutting behavior of hot mix and warm mix asphalt overlay on flexible pavements,” Int. J. Pavement Res. Technol., 2020. https://doi.org/10.1007/s42947-020-0057-5

[19] H. Alimohammadi, J. Zheng, A. Buss, V. R. Schaefer, and G. Zheng, “Rutting Performance Evaluation of Hot Mix Asphalt and Warm Mix Asphalt Mixtures by Using Dynamic Modulus, Hamburg Wheel Tracking Tests, and Viscoelastic Finite Element Simulations,” International Conference on Transportation and Development 2020, pp. 83– 94. https://doi.org/10.1061/9780784483183.009

[20] J. Zheng, H. He, and H. Alimohammadi, “Three-dimensional Wadell roundness for particle angularity characterization of granular soils,” Acta Geotech., vol. 9, p. 2020. https://doi.org/10.1007/s11440-020-01004-9

[21] H. Alimohammadi, K. Yashmi Dastjerdi, and M. Lotfollahi Yaghin, “The study of progressive collapse in dual systems,” Civ. Environ. Eng., vol. 16, 2020. https://doi.org/10.2478/cee-2020-0009

[22] H. Alimohammadi, J. Zheng, A. Buss, V. Schaefer, C. Williams, and Guangfan Zheng, “Performance Evaluation of Hot Mix and Warm Mix Asphalt Overlay Layers Based on Field Measurements and Finite Element Viscoelastic Simulations,” Transp. Res. Board Conf. 99th

Annu. Meet., 2020. https://annualmeeting.mytrb.org/OnlineProgramArchive/Details/13743

[23] H. Alimohammadi, A. Hesaminejad, and M. Lotfollahi Yaghin, “Effects of different parameters on inelastic buckling behavior of composite concrete-filled steel tubes,” Int. Res. J. Eng. Technol., vol. 6, no. 12, 2019. https://www.researchgate.net/publication/337856971_Effects_of_different_parameters_on_inelastic_buckling_behavior_of_composite_concrete-filled_steel_tubes

[24] H. Alimohammadi, M. D. Esfahani, and M. L. Yaghin, “Effects of openings on the seismic behavior and performance level of concrete shear walls,” Int. J. Eng. Appl. Sci., 2019. https://www.researchgate.net/publication/337596926_Effects_of_openings_on_the_seismic_behavior_and_performance_level_of_concrete_shear_walls

[25] H. Alimohammadi, “Finite element analysis of a Piezoelectric layered plate with different materials,” International Journal of Engineering and Applied Sciences, vol. 6, no. 7, 2019. DOI: 10.31873/IJEAS.6.8.2019.09

[26] H. Alimohammadi and M. Lotfollahi Yaghin, “Study on the Effect of the Concentric Brace and Lightweight Shear Steel Wall on Seismic Behavior of Lightweight Steel Structures,” Int. Res. J. Eng. Technol., vol. 6, no. 8, pp. 1358–1362, 2019. https://www.researchgate.net/publication/336846191_Study_on_the_Effect_of_the_Concentric_Brace_and_Lightweight_Shear_Steel_Wall_on_Seismic_Behavior_of_Lightweight_Steel_Structures

[27] H. Alimohammadi and M. Abu-Farsakh, “Finite Element Parametric Study on Rutting Performance of Geosynthetic Reinforced Flexible Pavements,” Transp. Res. Board, vol. 98th, 2019. https://trid.trb.org/view/1572248

[28] H. Alimohammadi and A. Memon "A Case Study of Mechanically Stabilized Earth (MSE) Retaining Wall Failure in the State of Tennessee; Recommendations for Future Design and Constructions" OSF Preprints, https://doi.org/10.31219/osf.io/uy76r

[29] H. Alimohammadi, V. R. Schaefer, J. Zheng, and D. White, " A full-scale field approach for evaluating the geogrid reinforcement effectiveness in flexible pavement", 22nd International Conference on Soil Mechanics and Geotechnical Engineering, 2022

[30] H. Alimohammadi, J. Tahat, " A State-of-The-Art Evaluation of Driven Pile Behaviors Using Pile Load Testing (PLT)", 101st Transportation Research Board Annual Meeting, TRBAM-22-01453, 2022, https://annualmeeting.mytrb.org/OnlineProgram/Details/17332

[31] H. Alimohammadi, " Effectiveness of Geogrids in Roadway Construction: Determine a Granular Equivalent (G.E.) Factor", Iowa State University, 2021, https://www.proquest.com/docview/2576937127

[32] H. Alimohammadi, " Rutting Behavior of Laboratory, Field, and Finite Element Simulated Hot Mix and Warm Mix Asphalt Overlays", Iowa State University, 2021.

[33] H. Alimohammadi, M. Abu-Farsakh, " Evaluating Geosynthetic Reinforcement Benefits of Flexible Pavement", 8th Annual Graduate Student Research Conference, 2019

[34] H. Alimohammadi and A. Memon "Failure Analysis and Recommendations For Improving Mechanically Stabilized Earth (MSE) Retaining Wall Design and Construction: A Case Study from Tennessee, USA" Transportation Research Board 103rd Annual Meeting, TRBAM-24-00338, 2024

[35] H. Alimohammadi and A. Memon "A Case Study of Failure Analysis of an MSE Retaining Wall in Tennessee: Lessons Learned and Recommendations for Reconstruction" OSF Preprints, 2023, https://doi.org/10.31219/osf.io/nf95e

[36] H. Alimohammadi and A. Memon "Forensic Investigation of Slope Stability Issues and Design Practices: A Case Study in Nashville, Tennessee" OSF Preprints, 2023, https://doi.org/10.31219/osf.io/9yx82

[37] H. Alimohammadi and J. Tahat "Evaluation of Driven Pile Using Pile Load Testing: A Case Study in the State of Ohio" Geo-Congress 2024 conference, 2024.

[38] H. Alimohammadi and J. Tahat "Evaluating Driven Pile Behaviors Through Case Study Experimental Pile Load Testing (PLT)" 48th Annual Conference on Deep Foundations, 2023.

[39] S. Satvati, H. Alimohammadi, M. Rowshanzamir, and S. M. Hejazi, “Bearing Capacity of Shallow Footings Reinforced with Braid and Geogrid Adjacent to Soil Slope,” Int. J. Geosynth. Gr. Eng., vol. 6, no. 41, p. 2020. https://doi.org/10.1007/s40891-020-00226-x

[40] H. Alimohammadi, J. Zheng, A. Buss, V. R. Schaefer, and G. Zheng, “Evaluating the Rutting Performance of Hot Mix Asphalt and Warm Mix Asphalt Mixtures by Using Viscoelastic Finite Element Simulations,” Int. Conf. Transp. Dev. 2020, https://doi.org/10.1061/9780784483183.009

[41] H. Alimohammadi, J. Zheng, V. Schaefer, J. Siekmeier, and R. Velasqueze, “Evaluation of Geogrid Reinforcement of Flexible Pavement Performance: A Review of Large-Scale Laboratory Studies,” Transp. Geotech., p. 2020. https://doi.org/10.1016/j.trgeo.2020.100471

[42] H. Alimohammadi and B. Izadi Babokani, “Finite element electrodynamics modeling of a layered piezoelectric composite shell with different materials by using numerical software,” ISSS J. Micro Smart Syst., 2020. https://doi.org/10.1007/s41683-020-00052-3

[43] H. Alimohammadi, M. D. Esfahani, “Investigating the Opening Effect of Constant Cross-Section and Various Forms of Seismic Behavior and Performance levels in Concrete Shear Walls” First international conference on civil engineering architecture and stable urban development, 2015.

[44] H. Alimohammadi, and M. Lotfollahi Yaghin “Evaluation of seismic properties of light weight concentric brace on seismic behavior of light weight steel structures” National Conference in applied civil engineering and new advances, 2014.

[45] H. Alimohammadi, and M. Lotfollahi Yaghin “Evaluation of seismic properties of lightweight steel frames coated with lightweight steel shear wall” First international conference on urban development based on new technologies and 4th national conference on urban development, 2014.

[46] H. Alimohammadi and A. Memon "Comprehensive Sinkhole Mitigation: A Case Study and Application of Compaction Grouting in Karstic Environments in in the State of Tennessee, USA" Journal of Civil Engineering Researchers, 6(2), 1–16. 2024 https://doi.org/10.61186/JCER.6.2.1

[47] H. Alimohammadi and A. Memon "Mitigation of A Sinkhole in Nashville, Tennessee: A Case Study with Compaction Grouting Approach". 2024. https://doi.org/10.31219/osf.io/63nyv

[48] H. Alimohammadi and A. Memon "Failure Analysis and Recommendations For Improving Mechanically Stabilized Earth (MSE) Retaining Wall Design and Construction : A Case Study from Tennessee, USA" Transportation Research Board 103rd Annual Meeting, 2024

[49] H. Alimohammadi and A. Memon "Case Study of Mechanically Stabilized Earth (MSE) Retaining Wall Failure in the State of Tennessee; Recommendations for Future Design and Constructions". Journal of Civil Engineering Researchers, 5(1), 52–65. https://doi.org/10.61186/JCER.5.1.52

[50] Ambily AP, Gandhi SR (2007) Behavior of stone columns based on experimental and FEM analysis. J Geotech Geoenviron Eng ASCE 133(4):405–415

[51] Andreou P, Frikha W, Frank R, Canou J, Papadopoulos V, Dupla JC (2008) Experimental study on sand and gravel columns in clay. Ground Improv 161(4):189–198

[52] Barksdale RD, Bachus RC (1983) Design and construction of stone columns. Report No. FHWA/RD 83/026 Federal Highway Administration 1:194