Vibro Systems
Site Improvement Begins With Hayward Baker Vibro Technologies

Vibro systems are used to solve a wide range of static, dynamic and seismic foundation problems through the use of depth vibrators to densify and/or reinforce the soils in situ.

The first vibratory method for the densification of deep, granular deposits was developed by the Keller Group and introduced into Europe in 1936. Known now as Vibro Compaction, and also referred to as vibroflotation, this classic technique paved the way for the development of Vibro Replacement (stone columns), effectively increasing the range of treatable soils to include fill materials, cohesive soils and mixed soils. More recently, the introduction of bottom feed Vibro Replacement has provided for enhanced soil displacement and allowed for stone columns to be constructed without the introduction of water.

Including the appropriate Vibro technique as part of the foundation design can often reduce construction schedules and project costs significantly, by permitting the use of conventional spread footings rather than a deep foundation system. Hayward Baker has the experience, expertise and resources to provide the right Vibro solution for your site improvement needs.

Depending on subsurface conditions and the degree of ground improvement required, Hayward Baker can offer a warranty for your project. Such was the case for the ITT buildings in Plymouth, Minnesota.

The building footprints were, in good part, underlain by a deep peat deposit. Removal of this organic layer and replacement with clean sand, which was then densified by the use of Vibro Compaction with gravel backfill, improved the soils to allow the building loads to be supported on shallow foundations with 10,000 and 12,000 psf bearing pressures.
Vibro techniques use specially-designed, poker-type depth vibrators. Extension tubes are added to allow vibrator penetration to treatment depths in excess of 100 feet below working grade. The vibrator assembly is typically supported from a standard crane or purpose-built hydraulic crawler crane. Treatment is accomplished over a two to three foot depth interval and the vibrator is then raised to the next level. This procedure is repeated over the entire depth of treatment.

The two primary deep vibratory techniques are Vibro Compaction and Vibro Replacement. Vibro Compaction is used to densify loose sands and gravels. In soils that do not respond well to vibration alone, improvement is achieved by the installation of stone columns using the Vibro Replacement technique.

Both of these techniques offer a technically-proven and cost-effective alternate to deep foundations, allowing a variety of structures to be supported on shallow spread footings. These structures include: Residential, Commercial and Industrial Facilities; Office Buildings, Schools and Hospitals; Wastewater Treatment Plants; Tanks; Bridges and Bridge Approaches, Highways and Overpasses; Dams; Embankments.

**The Vibrator**

The vibrator penetrates to depth by means of its weight and vibrations, sometimes accompanied by air and/or water jetting. Horizontal vibrations are generated at treatment depth with the use of eccentric weights that are rotated by means of electric motors rated up to 200 HP and eccentric forces up to 38 tons.

The motion of the vibrator is radial in the horizontal plane, creating a dynamic force in the direction in which soil is weakest. Since the vibrator is at the treatment depth, this is the most efficient use of the vibratory energy, resulting in the greatest densification.

The recent addition of variable frequency control enables Hayward Baker to tailor the most effective vibratory energy to the soil for maximum treatment efficiency.

**Benefits of Vibro Technologies:**

♦ Increased bearing capacity  
♦ Increased shear resistance  
♦ Reduced settlement  
♦ Mitigation of liquefaction and lateral spreading  
♦ Uniformity of site after treatment  
♦ Achievement of the specific degree of improvement required by the project  
♦ Cost and time savings over conventional systems  
♦ Can be applied close to existing structures  
♦ In situ treatment, thus avoiding excavation and replacement
Vibro Compaction

Vibro Compaction is used to densify clean, cohesionless soils. The action of the vibrator, usually accompanied by water jetting, reduces the inter-granular forces between the soil particles, allowing them to move into a denser configuration, typically achieving a relative density of 70 to 85 percent. Compaction is achieved above and below the water table.

The improved soil characteristics depend on the soil type and gradation, spacing of the penetration points and the time spent for compaction. Generally, the spacing is between 6 feet and 14 feet, with centers arranged on a triangular or square pattern. Compaction takes place without setting up internal stresses in the soil, thus ensuring permanent densification.

Once the vibrator has penetrated to design depth, treatment takes place at prescribed depth intervals. During compaction, clean, sand backfill is typically added from the ground surface to compensate for the reduction in soil volume resulting from the densification process. In this way, original site elevation is maintained. However, on sites where the planned final grade is below the existing grade, lowering of the site elevation may be desirable. In these instances, the ground surface is allowed to subside during the compaction effort. The surficial site soils are sometimes used as the backfill material.

Vibro Compaction permits the use of economical spread footings with design bearing pressures generally of 5 ksf up to 10 ksf. Settlement potential and seismic liquefaction potential are reduced. The required treatment depth is typically in the range of 15 to 50 feet, but Vibro Compaction has been performed to depths as great as 120 feet.

### Expected Results

<table>
<thead>
<tr>
<th>Ground Type</th>
<th>Relative Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sands</td>
<td>Excellent</td>
</tr>
<tr>
<td>Silty Sands</td>
<td>Marginal to Good</td>
</tr>
<tr>
<td>Silts</td>
<td>Poor</td>
</tr>
<tr>
<td>Clays</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Mine Spoils</td>
<td>Good (if clean granular)</td>
</tr>
<tr>
<td>Dumped Fill</td>
<td>Dependent On Nature of Fill</td>
</tr>
<tr>
<td>Garbage</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

Vibro Compaction improved the bearing capacity of the loose, sandy soils and mitigated liquefaction potential for construction of a 117,000 sq ft retail store on shallow foundations.

Very limited land availability required that a new airport on the West Indies island of Bequia be constructed on hydraulically-placed coral sand fill adjacent to the existing shoreline. Vibro Compaction was used to treat the 1.3M cu yds of loose material to reduce settlement and mitigate liquefaction potential.
Vibro Compaction Process

**Penetration**
At full water pressure the vibrator penetrates to design depth and is surged up and down as necessary to agitate sand, remove fines and form an annular gap around the vibrator. The water flow is then stopped or reduced.

**Compaction**
Under the action of induced horizontal forces the soil particles surrounding the base of the vibrator are rearranged to a denser state of compaction. The vibrator is raised incrementally as compaction is achieved.

**Refilling**
During compaction, either imported (A) or in situ (B) material is introduced. If in situ material is used, the surface of the area being compacted may be lowered 5% to 15% of the treated depth.

**Completion**
With an economical layout of compaction probes, an optimum improvement can be achieved. The surface of the improved area is then relevelled and densified with a surface compactor.

The Vibro Compaction Process:
- Increases bearing capacity and reduces foundation size
- Reduces foundation settlement
- Mitigates liquefaction potential
- Permits construction on granular fills

Profile of sand grains rearranged by Vibro Compaction. Volume reduction due to densification of non-cohesive soils may result in surface settlement of 5% to 15% of the treated depth.
Vibro Replacement

Cohesive, mixed and layered soils generally do not densify easily when subjected to vibration alone. The Vibro Replacement technique was developed specifically for these soils, effectively extending the range of soil types that can be improved with the deep vibratory process.

With Vibro Replacement, columns of dense, crushed stone are designed to increase bearing capacity, reduce settlement, aid densification and mitigate the potential for liquefaction, and improve shear resistance. As the Vibro stone column is formed, the crushed stone is laterally compacted against the surrounding soil. The dense stone can then aid in further transmitting vibration energy into the soil, assisting with densification in uniformly graded and/or silty sands. The Vibro stone column and the in situ soil form an integrated system having low compressibility and high shear strength. Excess pore water can readily dissipate through the Vibro stone columns, which act as vertical drains.

Vibro stone columns can be arranged to suit varying combinations of loads, soil types and performance requirements. Column spacing is generally in the range of 6 to 10 feet. The allowable loads on reinforced soil vary according to soil conditions and performance requirements, but in cohesive soils will generally fall in the range of 1 to 5 ksf. However, higher values (2 to 10 ksf) are possible in granular soils or where the rate of loading permits substantial consolidation to occur.

The Two Primary Methods of Vibro Stone Column Construction Are:

Wet, Top Feed Method (Replacement & Displacement)
In this technique, jetting water is used to remove soft material, stabilize the probe hole, and ensure that the stone backfill reaches the tip of the vibrator. This is the most commonly used and most cost-efficient of the deep vibratory methods. However, handling of the spoil generated by the process may make this method more difficult to use on confined sites or in environmentally sensitive areas.

Dry, Bottom Feed Method (Displacement)
This technique uses the same vibrator probes as standard Vibro Replacement, but with the addition of a hopper and supply tube to feed the stone backfill directly to the tip of the vibrator. Bottom feed Vibro Replacement is a completely dry operation where the vibrator remains in the ground during the construction process. The elimination of flushing water in turn eliminates the generation of spoil, extending the range of sites that can be treated. Treatment is possible up to a depth of 80 feet and is not inhibited by the presence of groundwater.

Expected Results

<table>
<thead>
<tr>
<th>Ground Type</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>Densification</td>
</tr>
<tr>
<td>Sands</td>
<td>Excellent</td>
</tr>
<tr>
<td>Silty Sands</td>
<td>Very Good</td>
</tr>
<tr>
<td>Non Plastic Silts</td>
<td>Good</td>
</tr>
<tr>
<td>Clays</td>
<td>Marginal</td>
</tr>
<tr>
<td>Mine Spoils</td>
<td>Excellent, Depending on Gradation</td>
</tr>
<tr>
<td>Dumped Fill</td>
<td>Good</td>
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<tr>
<td>Garbage</td>
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</table>

Bottom feed Vibro Replacement uses a hopper and supply tube to feed the stone directly to the tip of the vibrator.
The introduction of stone provides for a high modulus medium that transmits the horizontal vibratory force and stone backfill material farther into the ground, improving the ability to densify surrounding soil.

Top Feed Vibro Replacement Process

![Diagram of Top Feed Vibro Replacement Process]

**Penetration**
Assisted by water jetting, the vibrator penetrates to design depth under its own weight. The water jets are then adjusted to maintain an annular space around the vibrator.

**Replacement**
Crushed stone backfill is introduced in discrete lifts from the ground surface. Repenetration of each lift, and the horizontal forces of the vibrator, laterally compacts the stone against the surrounding soil.

**Completion**
This process is repeated up to ground level, forming a well-compacted, tightly-interlocked stone column surrounded by soil of enhanced density.

The Vibro Stone Column Process:
- Reduces foundation settlement
- Increases bearing capacity, allowing reduction in footing size
- Mitigates liquefaction potential
- Provides slope stabilization
- Permits construction on fills
- Permits shallow footing construction
- Prevents earthquake-induced lateral spreading

*At the Design Center of the Americas site in Dania, FL, the use of a lower horsepower vibrator allowed Vibro Replacement to be performed close to an existing building that had been constructed on soils also treated by Vibro Replacement.*
Design Considerations

The design approach for Vibro technologies will generally be governed by one or more of the three major categories of site improvement:

♦ Shear resistance
♦ Settlement control
♦ Mitigation of liquefaction and lateral spreading

Requirements for Design

Design of the Vibro program requires information on:

♦ Total loads (structure, surcharge, live, wind and seismic)
♦ Soil type (variation, stratigraphy, groundwater location)
♦ Type of footing/slab design
♦ Structural settlement tolerance
♦ Site restrictions and limitations

To address the above issues, the Vibro program is designed such that the zone of influence of the vibratory probe ensures the necessary soil densification and/or reinforcement.

Increased Bearing Capacity

Bearing capacity is a function of the soil’s shear strength which is derived from the soil’s angle of internal friction (φ) and/or cohesion (c). The Vibro systems increase the allowable bearing capacity by increasing the effective φ angle.

Vibro Compaction densifies cohesionless granular soils, therefore increasing the angle of internal friction directly. The allowable bearing capacity is calculated with conventional procedures using the improved angle.

Vibro Replacement constructs dense, Vibro stone columns in the zone requiring improvement. The allowable bearing capacity can be calculated by a variety of methods, such as the one developed by Priebe in “The Design of Vibro Replacement”, Ground Engineering, December 1995. If any of the in situ soils are granular, their improved value should also be accounted for in the design.
Reduced Settlement
Settlement is a function of the soil’s modulus and consolidation character. Vibro systems decrease the settlement that will occur beneath a proposed foundation by either directly increasing the in situ soil’s modulus value and/or by constructing high modulus Vibro stone columns in a grid pattern beneath the planned foundation.

Vibro Compaction densifies cohesionless granular soils, thus increasing the soil’s modulus value directly. The settlement is calculated with conventional procedures using the improved modulus value.

Vibro Replacement constructs high modulus dense Vibro stone columns in the zone requiring improvement. The anticipated settlement can be evaluated by a variety of methods, such as the Priebe method. This method provides an improvement factor based on the stone column’s angle of internal friction and the percentage of the treatment zone replaced by stone (area replacement ratio). In addition, if any of the in situ soils are granular, their improved parameters should also be included in the design.

A well-designed Vibro program, tailored to the in situ soils and the proposed construction, is the critical first step in successful site improvement.
Design Considerations

Liquefaction Prevention
Seismic motion causes pore pressure to increase. When the pore pressure increases to equal interstitial grain-to-grain stresses, liquefaction is initiated. The soil then loses all shear strength, resulting in bearing failures and slope instability, followed by large deformations (horizontal and vertical).

To combat this phenomenon, site improvement by densification has proven to be the most effective solution. Densification will increase interstitial stresses beyond pore pressure increase potential, thus preventing liquefaction and settlement.

Vibro stone columns can offer the greatest protection by densifying and reinforcing the ground, and by providing an increased drainage potential through the stone column. Although stone columns enhance vertical drainage during a seismic event, drainage alone is not enough. Densification is required to preclude excessive settlements and offers the most secure remedy to multiple ground accelerations (aftershocks).

Assessing Site Liquefaction Potential
The most basic procedure used in engineering practices for the assessment of site liquefaction potential is that of the “Simplified Procedure”, originally developed by Seed and Idriss (1971, 1982) and subsequent refinements by Seed and others. The procedure primarily compares the cyclic resistance ratio (CRR) [the cyclic stress ratio required to induce liquefaction for a cohesionless soil stratum at a given depth] with the earthquake-induced cyclic stress ratio (CSR) at that depth from a specified design earthquake, defined by peak ground surface acceleration and an associated earthquake moment magnitude.

These earthquake parameters are developed by seismologists upon review of earthquake probability maps, site subsurface conditions, and risk potential for the structure. The regional differences are distinct. West coast earthquakes, for instance, are potentially of higher magnitude than those anticipated on the east coast; however, an east coast earthquake will likely affect a much larger area. Updated building codes also offer some guidance.

In the many areas of North and South America susceptible to earthquake activity, the densification and reinforcement provided by Vibro techniques can mitigate the liquefaction and lateral spreading associated with a seismic event.

The figures at right show a comparison of CSR and CRR to the measured in situ strength of the soil as determined by Standard Penetration Tests (SPTs) or Cone Penetrometer Tests (CPTs). The graphs indicate that for a magnitude 7.5 earthquake, liquefaction potential can be diminished when the soil stratum is improved to 20 to 30 blows per foot, corrected SPT values, or to 100 to 150 tsf, corrected CPT tip resistance. The fines content (% passing the No. 200 sieve) plays an important role in assessing the potential for liquefaction and subsequent design of a ground improvement program.

**Embankment Subgrade Improvement**

Where embankments are to be constructed, Vibro stone columns, installed through the calculated failure surface, can increase the slope stability safety factor provided the columns can attract sufficient loading to increase shearing resistance.

The shear strength of treated soil depends on the shear strength of the untreated soil, the transverse shear strength of the columns, the area replacement ratio and the load conditions. Design methods typically use some average shear strength based on these parameters for analysis. Stability calculations are then analyzed by Bishop’s, Janbu or other numerical analysis methods.

Of particular interest is the case of a planned embankment over soft soils. As the embankment is constructed over the Vibro stone columns, stress concentration occurs in the columns due to their modulus value being much greater than the soft, surrounding in situ soil. This stress concentration results in a high vertical stress in the column, thus greatly increasing the columns’ shear resistance. Stress concentration factors of three or greater are common.
Quality Control & Quality Assurance

Comprehensive quality control and quality assurance plans are an essential part of the successful Vibro program. The QA/QC program is the best way to assure that the work will provide a foundation system that will meet the client’s needs.

The project execution program outlines the procedures for the work, and the QC program documents these procedures as well as the testing conducted. During the work, real-time monitoring of essential parameters is performed. The QA program defines the review of aspects of the work and testing as well as addressing conformance issues.

Production Monitoring
For both Vibro Compaction and Vibro stone column construction, the quality of the in situ product is ensured during the work by monitoring and recording of:

♦ Quantity and quality of backfill added
♦ Vibrator amperage draw
♦ Treatment depth

Vibrator amperage draw is a qualitative measure of ground improvement. As densification occurs, the ground restricts the horizontal movement of the vibrator, causing an increased draw to maintain frequency. This measure is available in real time to the operator to optimize densification procedures.

Post-Construction Testing
Depending on the predicted improvement of the in situ soils, the effectiveness of Vibro treatment can readily be verified by using one or more of the standard test methods such as:

♦ Standard penetration testing (SPT)
♦ Cone penetrometer testing (CPT)
♦ Dilatometer testing (DMT)
♦ Load testing
♦ Shear wave velocity profiling

<table>
<thead>
<tr>
<th>CPT Results</th>
<th>Soil Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qc (tsf)</td>
<td>Pre-Treatment</td>
</tr>
<tr>
<td>EL +10</td>
<td>Backfill Grade</td>
</tr>
<tr>
<td>EL +5</td>
<td>Post-Densification</td>
</tr>
<tr>
<td>EL 0</td>
<td>Final Grade</td>
</tr>
<tr>
<td>EL -25</td>
<td>Maximum Treatment Depth</td>
</tr>
</tbody>
</table>

Recommended test locations for densification evaluation.
At a marine research facility in St. Petersburg, FL, Vibro Replacement was performed to densify the overlying loose sands and underlying silty sands and reinforce a soft, organic layer (bay bottom) to support an allowable soil bearing pressure of 4,500 psf.

In cohesive soils treated by Vibro stone columns, full-scale static load tests may be the best way to assess the improved soil quality. The size of the test pads and the magnitude of the test load can vary according to the Vibro stone column layout, treatment depth, load and type of structure, safety assessments and economics. Commonly used test pads are between 25 and 100 sq ft in area, with loads as great as 750 tons.

The cost and time involved in performing full-scale static load testing can often be prohibitive, especially on sites where multiple tests are required. However, the Statnamic™ load test system* overcomes this problem. The Statnamic method generates the test load by using a fast-burning fuel to accelerate a weight away from the test pad. The equal and opposite forces on the test pad can be up to 20 times the weight being accelerated. This method has proven to mirror traditional static load-deflection results in basically granular soils and will realize a net savings on many projects.

*Statnamic™ is a registered trademark of Birminghamer Foundation Equipment, represented in the USA by Applied Foundation Testing Inc.
Selected Projects

**State Route 201 Crossing, I-15 Corridor, Utah**
Subsurface soils at the bridge abutments of the SR 201 Jordan River crossing consist of up to 16 ft of clay and sand fill underlain by interbedded layers of sand and clay, with groundwater encountered at 1.5 to 4.5 ft. Vibro Replacement for ground improvement was based on a magnitude 7.5 earthquake generating a peak horizontal ground acceleration of 0.67g. Vibro stone columns were installed to densify and reinforce a liquefiable sand layer at 25 to 31 ft below grade to meet a post-earthquake factor of safety of 1.1.

**Interstate 44, Tulsa, Oklahoma**
Oklahoma DOT planned to add 2 new lanes along a 2-mile stretch of I-44 through Tulsa that is built on a soil embankment. Since the area was right-of-way restricted, and the silty clay subsurface soils presented a potential global instability problem, the DOT specified cast-in-place retaining walls supported by driven piles. This would maximize available space for the new roadway and ensure the stability of the walls. As a value-engineered alternative, a mechanically stabilized earth wall was constructed, supported by bottom feed Vibro stone columns. This option met project specifications while realizing a cost savings over the original method.

**Amgen Manufacturing Facility, Longmont, Colorado**
A new 225,000 sq ft manufacturing facility, constructed on drilled shafts, was designed with a structural slab to support floor loads of up to 5 ksf. A design/build alternative of bottom feed Vibro stone columns improved the loose clays and silts beneath the slab area to meet the 0.5-inch total settlement criterion. This allowed slab-on-grade construction at a significant cost savings.

**Wantagh Parkway, New York, New York**
To ease traffic congestion to and from Jones Beach, New York City’s main summer getaway resort, New York DOT planned to replace the existing, 2-lane bridge over Goose Creek, Long Island with a new, 4-lane structure. Vibro stone columns were installed to improve the load bearing capacity of the existing abutments. To maintain single-lane traffic flow, work was accomplished in a two-phase operation during the off-season. The 3-ft diameter stone columns were installed through the sands and gravels to a depth of 55 ft, resulting in an average 200 tsf CPT tip resistance, well in excess of project requirements.

**USF Bioscience Center, Tampa, Florida**
The soil profile at the site of the new University of South Florida Bioscience Center is typical of central Florida, with 30 to 50 ft of sands overlying solution-prone karstic limestone. Vibro Replacement was performed in the upper sands for increased bearing capacity and settlement control. For sinkhole pre-treatment, selected vibro probes penetrated to the limestone to collapse any voids that existed in the overburden. If a surface sinkhole then followed, the depression was filled with sand backfill and additional Vibro Replacement performed.

As part of a major renovation program for New Hampshire’s Manchester airport, extensive Vibro Compaction has been completed beneath the footprint of several new structures, including the main terminal and a multi-story parking deck, to improve the clean, loose sands and mitigate liquefaction potential.

At the Port of Port Arthur, TX, Vibro stone columns were installed to 45 ft to reinforce and enhance drainage of the clay and speed consolidation from a temporary surcharge fill, increasing overall strength for construction of a new 50,000 sq ft container storage site.

At Pacific Bell Park, home of the San Francisco Giants, Vibro stone columns were installed between in-place tie beams to improve bulkhead stability along the China Basin Channel and eliminate the potential for lateral spreading in the sand fill section of the bay side seawall.
Pioneer Middle School, Porterville, California
From engineering analyses conducted prior to construction of a new, multi-use school auditorium, up to 8 inches of total settlement and 3 inches of differential settlement under a peak ground acceleration of 0.22g were predicted during a seismic event. Top feed Vibro stone columns were installed to a depth of 30 ft beneath the building footprint to mitigate the liquefaction potential.

Shores of Waterstone, Oxford, Michigan
Waterstone Lake was created in what was previously an open pit gravel quarry. The pit had been excavated and dredged to depths in excess of 30 ft below the water table. After the lake was created, the sand fraction of the gravel extracting operation was sluiced back into the lake, forming a very deep, loosely-deposited shoreline. To allow construction of a housing development along the shoreline, Vibro Compaction was performed at 50 home sites, providing a minimum relative density of 60 percent to support the 4,000 psf foundation loads.

IMSS Hospital, Manzanillo, Mexico
In 1995, a 7.6 magnitude earthquake hit Manzanillo, causing widespread liquefaction and structural damage to the port and a number of structures. Serious damage to the existing hospital led the Mexican Social Security Institute (IMSS) to construct a new one. In order to prevent liquefaction, over 1,500 stone columns were installed to an average depth of 21 ft at the new site using the top feed, Vibro Replacement process to densify the loose sands beyond their liquefaction threshold, and also provide ground reinforcement, allowing for a higher design bearing capacity.

West Ashley High School, Charleston, South Carolina
Many areas of the eastern United States are vulnerable to significant earthquake activity. Ground improvement to mitigate liquefaction potential is increasingly being included in new construction, particularly for public use facilities. For a new, 2-story high school, both structural settlement and potential liquefaction of the underlying 20 ft of silty, clayey sands were addressed by Vibro Replacement. The installation of 42-inch diameter top feed Vibro stone columns beneath the foundations not only mitigated the liquefaction potential but also reduced foundation settlements to less than one inch under the design loads. Area treatment between the foundations consisted of a continuous pattern of 32-inch diameter Vibro stone columns.

Boca Raton Community Hospital, Boca Raton, Florida
Facility upgrade at the Boca Raton Community Hospital involved the phased construction of two, 4-story buildings, a 4-story parking garage and a retail drug store. In the first phase of work, Vibro Compaction densified the loose sands beneath a 21,275 sq ft building pad to a depth of 35 ft to achieve a minimum bearing capacity of 6,000 psf. The use of a smaller vibrator close to the existing buildings addressed any concerns of potential, vibration-induced damage while still ensuring that overall post-construction criteria of 0.75 inches of total settlement and 0.5 inches of differential settlement were met.