# Update on In Situ Testing for Ground Modification Techniques

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In situ testing has played a major role in the growth of ground modification in the United States. If the in-place soil is inadequate for construction, the engineering profession is frequently designing for the ground to be modified, rather than using a deep foundation that bypasses the inadequate soil or removing and replacing the problem soil. There has been little change in the status of in situ testing for ground modification for construction purposes. However, a new field of environmental geotechnical engineering has developed, bringing with it a need for testing of the modified ground for existing and emerging technologies. Recommendations for additional research and development in the area of in situ testing for ground modification are included.

Ground modification is the in-place controlled processing of existing materials to form part of a geotechnical construction system. This paper discusses how in situ testing has assisted the rapid growth of ground modification techniques in the United States. Well-defined quality assurance/quality control programs, backed up by appropriate in situ testing techniques, are now possible. Design engineers can now determine minimum settlements or maximum relative density criteria, prepare plans and specifications, and, by in situ testing, ascertain that the soil has been adequately treated to meet these requirements. Ground modification contractors using in situ testing are now able to determine when specifications are met and revise their construction procedures, when necessary.

An overview is given of the current status of some ground modification techniques including Dynamic Deep Compaction; vibrocompaction; vibroreplacement; vibrodisplacement; and cement, chemical, compaction, and jet grouting. Limitations regarding specific ground modification techniques and in situ testing are discussed and recommendations for future research needs are presented. *Soil Improvement—A Ten Year Update* (*1*) is a report of the ASCE Geotechnical Engineering Division's Committee on Placement and Improvement of Soils. These ground modification and many other techniques and in situ tests are included along with 10 major case histories on soil improvement. This is still a good, current reference for professionals contemplating designing or constructing with ground modification technologies.

## IN SITU TESTING

### Standard Penetration Testing

Standard penetration testing is the technique most commonly used to determine initial soil properties at a site. However, unless continuous standard penetration tests are specified, thin strata may be missed, which could influence the method selected for improving the soil. The initial N value, the type of material to be treated, the depth of treatment specified, the elevation of the groundwater, and so forth, are all factors to be considered in determining the possibility and ground modification method of reaching the specified N value criteria. The standard penetration test samples should have sieve analyses performed, particularly if the three most silt- and clay-sensitive techniques (vibrocompaction, chemical grouting, and compaction grouting) are contemplated.

### Cone Penetration Testing

Cone penetration testing presents a continuous soil profile with relative strength parameters. On critical, large projects, specialty ground modification contractors have supplemented the design soils reports by using cone penetration testing before, during, and after soil improvement. Spacings as close as a 50-ft square grid pattern have been used. The before testing vividly points out abnormalities of the site and allows the specialty contractor to plan the soil improvement program. The testing during the actual work gives assurance that the planned program is succeeding and indicates whether changes in spacing, additional energy input, or localized retreatment are necessary. The after-treatment cone penetration tests verify the success of the program. However, even in granular formations, a time lag has been noted in the improvement in the cone tip resistance reading (*2–5*). The cone testing apparatus, added to conventional drilling rigs, is limited by the reaction weight of the rig, which is normally less than 10 tons; this has hampered penetration to the required depth, particularly after soil improvement has been accomplished. Electric Dutch Cone rigs are available with reaction weights of 23 tons that have been able to penetrate over 80 ft in densified granular soils where the cone tip resistance has uniformly exceeded 150 tsf.

### Dilatometer

The flat plate dilatometer (*5,6*) is an innovative technique and an excellent supplement to cone penetration testing, particularly for critical structures where differential settlement is the main criterion. Results from the dilatometer are expressed in terms of the three index parameters: material index, $I_D$, related to the soil type; horizontal stress index, $K_D$, related to in situ $K_O$, coefficient of earth pressure at rest; and dila-

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tometer modulus, $E_D$, a parameter related to soil stiffness. Quantitative estimates of $K_O$, $S_u$ (undrained strength), 0 (friction angle for sands), OCR (overconsolidation ratio), and M (the constrained modulus) can be obtained from the empirical correlation with the dilatometer's $I_D$, $K_D$, and $E_D$. Sometimes, the strata are so densified that the DMT blade cannot be pushed by a drill rig. Then preboring is performed down to the specific zone to be tested rather than continuous testing from the surface as done prior to densification.

### Pressuremeter Test

The pressuremeter test has extensive application for ground improvement evaluation, offering the advantage that estimates can be made of the lateral stress, the moduli, and the shear strength (*7*).

## GROUND MODIFICATION TECHNIQUES

### Dynamic Compaction

Dropping weights onto the ground from various heights for soil improvements is called dynamic compaction, pounding, dynamic consolidations, and so forth and has a long historic background, with reports of the Romans using this method. The first documented project in the United States was in 1871, when a cannon was filled with lead and used to densify the soil beneath the foundations of the Saint George Mormon Temple, St. George, Utah (*8*). The late L. Menard's publication in 1975 (*9*) rekindled interest in this technique. However, through the late 1970s there was relatively limited use of dynamic compaction in the United States. This is demonstrated by the absence of relevant case histories in the ASCE's 1976 Bicentennial Report on *Soil Improvement, History, Capabilities and Outlook* (*10*) and the few case histories in Mitchell's 1981 "Soil Improvement—State of the Art Report" (*11*). In the 1980s, however, over 250 projects were performed in the United States, due to the economy of this technique and the capability of assessing the improvement of the soil by in situ testing. The publication by Lukas (*12*) in July 1986 for the Federal Highway Administration has increased the use of this system for highway construction. Some of the major contributions of Lukas's publication are as follows:

1. The grain size grouping of soils into three zones depending on their suitability for improvement by dynamic compaction;
2. The applied energy requirements in tonne-m/m$^3$, depending on the type of deposit being improved; and
3. The upper bound test values for standard penetration test, cone preparation test, and pressuremeter test after dynamic compaction.

Current practice in the United States involves the use of weights between 8 and 20 tons dropped from heights of up to 100 ft with a single line attachment from specially modified cranes. Some of the limitations of dynamic compaction have been the safety problems involved with dropping weights from these heights, flying debris, the damage that can be caused by the shear, compression and Raleigh waves generated by this technique, and the limit in the depth of influence obtainable by this method. Menard's original proposition, that the depth of influence is equal to the square root of the weight times the height of drop, has been modified by Leonards et al. (*13*), Lukas (*12*), and other authors. Current practice is to use a modification factor, varying between 0.3 and 0.7 depending on the soil type, to determine the predicted depth of influence.

The uses of dynamic compaction will continue to grow, primarily because of the relative economy of this method with cost conventionally starting at \$1.00/ft$^2$ of surface area densified, coupled with the relative speed with which this ground modification technique can be performed.

Dynamic compaction for improving nonhomogeneous fill, such as sanitary landfills, mine spoils, and building debris, will require better in situ testing methods. Standard penetration testing, cone penetration testing, pressuremeter, and dilatometer are of limited use in these materials, in the writer's opinion. One method that needs additional research and development for testing of nonhomogeneous fill is shear wave velocity, using the weight as the energy source and placing transducers around the site and monitoring before and after the densification. This would allow a determination of the relative cross site improvement, which then could be correlated with the potential site settlement characteristics.

### Vibrocompaction, Vibroreplacement, and Vibrodisplacement

The vibrosystems use a depth vibrator to densify granular soils horizontally. The vibrator is a hollow steel tube containing an eccentric weight mounted on a vertical axis that produces horizontal vibrations. The most recent equipment innovation is the use of vibrators to produce higher centrifugal forces so the probes can be spaced further apart, thus making greater economy possible. The vibrocompaction system was first developed in Germany in the 1930s, and its first commercial application in the United States was in Cape May, New Jersey, in 1948. Vibrocompaction improves the density of loose sands as long as the sands do not contain more than 12 percent silt or 3 percent clays. The vibrations liquify and realign the sand grains, causing a densification of the sand. Additional sand could be added around the perimeter of the vibrator, or the entire site could be dropped as the densification takes place.

The next major development of the vibrosystems was vibroreplacement, or stone columns, where the addition of stone backfill around the vibrator was used to treat nonhomogeneous strata, with the sands being densified and cohesive soil replaced and reinforced. The jetting action of the vibrator in the installation process washed out the cohesive material, which was replaced by stone around the perimeter, and diameters 3 to 4 ft were created by a single probe. Because of potential environmental problems with the fines-laden jetting water being disbursed across a site, a dry, bottom-feed method, labeled vibrodisplacement, was developed to place the stone at the tip of the vibrator. Its first major project in the United

States was the Steel Creek Dam (*14,15*). The use of the vibrosystem to improve sites is well documented in the literature. One major publication (*16*), sponsored by the Federal Highway Administration, gave more confidence to designers of stone columns for highway construction. These columns of stone could densify loose granular soils (reducing the risk of liquefaction), could treat mix granular and cohesive strata, and reduce the total and differential settlement under highways, bridge approaches, and so forth. The vibrodisplacement method now can accomplish the same objectives but with more concern for the environment.

In situ testing of granular soil, improved by the vibrocompaction system using the standard penetration test and the cone penetration test, is a common and reliable engineering practice. However, when soils are replaced or displaced by stone backfill, a hybrid system is created. Priebe (*17*) and others give criteria for designing this hybrid system, and load tests have proven to be an accurate method of verifying design assumptions.

A symposium (Design, Construction and Testing of Deep Foundation Improvements: Stone Columns and Other Related Techniques) sponsored by ASTM was held in Las Vegas, Nevada, on January 25, 1990. Many of the 22 papers presented describe the testing and instrumentation of stone columns. The proceedings were published in 1991 (*18*) and are required reading for consultants contemplating ground modification by the use of stone columns.

## Grouting

Grouting can generally be described as the injection of pumpable materials into a soil or rock formation to change the physical characteristics of the formation. The five types of grouting generally recognized and their methods are shown in Figure 1.

### *Slurry Grouting—Intrusion*

Although the oldest form of goruting, in situ testing methods for slurry grouting are still primitive, as are some of the other fundamentals of this type of grouting. The second century of slurry grouting has seen the beginning of computerization, while the debate continues as to the correct water/cement ratio, the proper drilling method, the proper pumping pressure, and so forth (*19,20*). The basic issues remain. How does the particular grout travel through the rock or soil, and when is a formation adequately grouting to satisfy the project requirements? Preliminary research has shown that, with the use of acoustic emission, it is feasible to plot where the grout is traveling through the medium (*21,22*). More development in this area is needed. Acoustic emission can also detect when hydrofracturing occurs in formations being drilled and grouted. In addition to being a useful safety tool for new and existing structures, particularly dams, this technique can allow site-specific group pressure to be used rather than relying on rules of thumb.

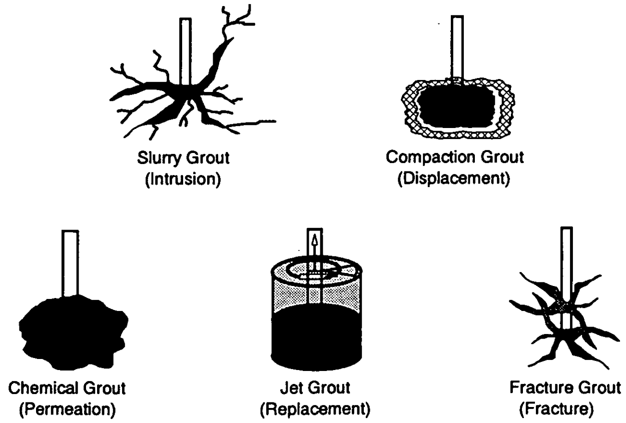

**FIGURE 1 Five types of grouting.**

The introduction of the finer-grind cements into the industry (*23–25*) gives another tool for better grouting of fractures, fissures, and seams in rock and for penetrating finer granular soils.

### *Compaction Grouting—Displacement*

Compaction grouting is the only ground modification technique developed in the United States. It uses low-slump grout under high pressure to densify soil, and its success depends on keeping the bulb of grout intact to densify and displace soils. In addition to arresting ongoing foundation settlement and controlling settlements caused by soft ground tunneling (*26*), there is a growing use of compaction grouting for preconstruction site improvement and treating liquefiable soils (*27,28*). Similar to other ground modification techniques that use inclusions to densify soils, testing in the center of the grid pattern can show the degree of improvement, but the results will be conservative. Better testing methods are needed to evaluate the soil-grout hybrid created. Byle et al. (*29*) describe how this in situ testing method was used on one project.

### *Chemical Grouting—Permeation*

In the 1970s the potential cost savings of using chemical grouts for stabilizing granular soils for subway construction encouraged the funding of federal research. As a direct result of this research, the mechanics of fluid grout permeating into granular soils are the best researched of all grouting types. In underpinning a portion of the Pittsburgh subway, crosshole shear wave velocity and crosshole radar testing for quality control were successfully used (*30*).

### *Jet Grouting—Replacement*

There are three main types of jet grouting: single rod, double rod, and triple rod. Single rod horizontally injects cement into a formation to form a soil-cement matrix as strong as the weakest strata it encounters; the double rod uses an air sheath to protect the slurry and permit a larger diameter to be created; and the triple rod system uses horizontal, high-pressure water jets protected by air to remove soils and replaces it with Soilcrete, a designed cementitious material injected vertically through the center rod at relatively low pressure. This system has been used commercially in Japan since the early 1970s, moved into Europe in the late 1970s, and was introduced in the United States in the early 1980s. Its uses in the United States have been mainly for underpinning, excavation support, and groundwater control (*31,32*), with the majority of the work being accomplished since 1987.

Soilcrete differs with each type of jet grouting, the characteristics of the cement grout injected, the rate of withdrawal, and the rate of rotation of the rods, the type of soil being treated, the groundwater, and so forth. Most testing has been performed by placing jet grouting elements adjacent to the site of the proposed project and by excavating and sampling these elements to determine diameters, strengths, and permeability. This, coupled with in-place sampling of the injected grout and waste, has determined which modifications to perform for the actual program.

## COMBINING GROUND MODIFICATION TECHNIQUES

Because each ground modification technique has its advantages and limitations and specific cost and time considerations, more and more construction projects are being performed by combining ground modification techniques to take advantage of the technical and economic advantages of each. Typical case histories follow.

### St. John River Power Park, Jacksonville, Florida

The ground modification for this 20-acre site combined dynamic compaction and compaction grouting to improve the up to 55 ft of loose sand over limestone (*22*). In addition to extensive standard penetration tests, over 80,000 linear ft of electric Dutch cone tests and 500 dilatometer tests were performed.

### K-D Tool Company, Waterboro, South Carolina

To allow the loose sand underneath an existing building to take the dynamic and static loads necessary for a relocated die forge operation, compaction grouting was used to improve the overall density of the soils in the affected area. Then chemical grouting was used for soil strength improvement and water control purposes beneath the four die forge hammers. Resonant column tests were performed to find the range of achievable shear moduli and crosshole seismic tests before and after the grouting to ascertain the soil improvement (*33,34*). The vibration measurements, made 2 and 14 months after the hammers were in operation, were in the range predicted during design, and no adverse settlement was noted.

### Steel Creek's Dam Foundation, Department of Energy's Savannah River Plant

This 2,000-ft-long embankment dam, which rises 85 ft above the original streambed, required extensive foundation treatment before dam construction. This included a slurry concrete cutoff wall to a depth of 140 ft, extensive cement grouting of the calcareous bedrock beneath the dam, and dynamic compaction of the 200,00-ft$^2$ valley floor using both a 19-ton weight and a 32-ton free-fall system to densify the loose sands. Extensive cone penetrometer and standard penetration tests verified that the average effective depth of treatment was 33 ft. At certain locations this then required stone columns to be placed to a depth of 60 ft by preaugering through the dynamically compacted sand and placing stone columns by the dry, bottom-feed method. The loose soils on both abutments were also densified by this vibrodisplacement technique (*14*).

### U.S. Navy's Trident Facility at St. Mary's, Georgia

A detailed performance specification was prepared for soil densification for settlement control as well as for prevention of liquefaction from both earthquake and blast possibilities. A combination of dynamic compaction, vibrocompaction, vibroreplacement, and compaction grouting was used to densify the soil. Before densification, electric dutch cone and dilatometer tests gave a profile of each of the sites. Then a decision was made to which densification method to use on this lump sum contract. After densification, testing was performed to verify that the specified results were obtained or to indicate where additional densification was necessary (*35*).

## RESEARCH AND DEVELOPMENT NEEDS

The following are four areas where additional research and development in situ testing are required for modified ground.

1. Fills: More and more highways and other structures are being built over sanitary landfills, construction, and miscellaneous fills. In the writer's opinion there is no adequate method of testing these heterogenous fill materials and determining their properties before, during, or after ground modification.
2. Ground modification by inclusions: Many of the ground modification techniques require inclusions of an engineered material into an unsuitable soil to improve the soil. These methods include vibrocompaction, vibroreplacement, dynamic compaction (when stone is driven into the ground), and all grouting methods (slurry, chemical, compaction, jet, and fracture). Current in situ testing methods measure the improvement in the existing ground normally at a location furthest from the points of the inclusion and in effect monitoring the weakest point in the improved soil strata. This leads to conservative design, which could be made more economical if in situ testing methods were developed to monitor the hybrid soil-inclusion system.
3. Postconstruction monitoring: Soils beneath foundations are modified to meet specific criteria such as minimum settlement, density, and so forth, and in seismic zones, protection from liquefaction. However, in the United States it is rare for the designer to provide monitoring or in situ testing to determine the lifetime movement of the improved soil or the effects on the improved soil from an earthquake. Economical in situ testing and monitoring methods are needed for foun-

dations built on improved soil for the life of the structure and the effects of natural phenomena, such as earthquakes.

4. Remediation: As the geotechnical engineering and construction practice moves ahead in remediation of contaminated soil and rock, many new ground modification techniques are being developed for cleaning up the environment, such as in situ vitrification, in situ vapor stripping, electric kinetics, in situ solidification, in situ stabilization, in situ fixation, freezing, bioremediation, pump and treat, surfactant flushing, and so forth. The environmental geotechnical community has a major thrust in development of ground modification techniques that can treat or remove the contaminants to a level set by regulations. However, little research and development has been done on these in situ techniques and how the contaminant and its removal affects the soil properties before, during, and after regulatory cleanup.

## SUMMARY

Each ground modification project that uses proper in situ testing and reports the results expands the profession's knowledge of these techniques.

## CONCLUSION

The greater acceptance by the consulting engineer of newer methods of in situ testing, particularly cone penetration testing, dilatometer, acoustic emission, and crosshole shear wave velocity, has prompted the growth of the ground modification industry.

Currently in the design of a foundation, if soil conditions dictate other than a conventional spread footing, the engineer can design a deep foundation or a system to modify the ground that lets the client realize possible savings in construction costs and time. The client has to assume an active role as part of the decision-making team, beginning with the initial decision to spend additional funds for the costs of in situ testing to establish the feasibility of ground modification.

The consultant must keep abreast of current technology so that criteria can be established to determine whether modified soil has met project requirements. Knowledge of all in situ testing methods and required test results is needed to determine testing feasibility and applications of ground modification methods.

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