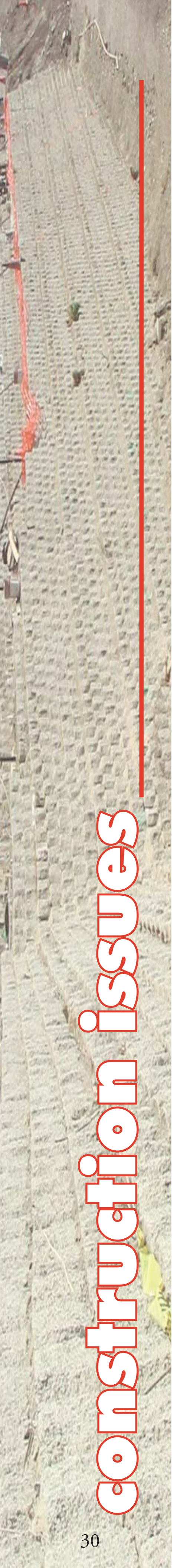

Compaction Grouting for In-Situ Ground Improvement

By Jeffrey Geraci, P.G., C.E.G.

Compaction grouting is a well-established method of *in-situ* soil improvement, and can also be used to lift and level structures founded on poor foundation soils. It is primarily used to densify weak foundation soils, although is often used for many other treatment objectives, including lifting and releveling of structures, filling sinkholes and solution cavities, increasing capacity of piles, mitigation of soil piping, and mitigation of soil liquefaction potential. Inherent in the compaction grouting process is the ability to work in and around existing structures and infrastructure elements, allowing for subsurface soil improvement without the need for structure demolition.

Mechanics

Compaction grouting is a mechanical process that involves injection of stiff soil/cement grout below grade under high pressure in order to displace nearby surrounding soil. A bulb-shaped grout inclusion (*Figure 1*) is typically formed at each point of injection. Injection casing is usually set to the base of the interval to be treated, and then withdrawn a short distance (typically 1 to 5 feet) to open the first pumping interval or "stage". Once one or more terminal pumping criteria are met, pumping at that stage will cease, the casing is withdrawn to the next stage, and the process repeated. This sequence continues until the target soil profile has been treated, or lack of overburden pressure at shallow treatment depths (3 to 5 feet below the ground surface) results in rapid surface uplift. *Figure 2* shows a typical compaction grouting treatment profile.

The grouting process makes use of available confining pressure in the target soil mass, which accommodates the injected grout by consolidation until the force exerted by continued bulb expansion exceeds the local confinement. At that time, the ground surface begins to bulge above the grout bulb, and any further grout injection is translated into uplift of the overlying soil and structures.

Compaction grout applies a very large load to a small area for a short time, but in doing so, rapidly accelerates the consolidation rate of the soil near the injection. Improvement in a large area is achieved by making a series of injections, commonly in a uniformly spaced array. Effective injection spacing can be on the order of 8 to 10 feet, although may be somewhat tighter in the event of shallow treatment. Temporarily, the grouting pressure can exceed the soil overburden weight because the reaction force confining the grout is the result of both the weight and the shear resistance of the soil displaced above the injection.

A variety of ground conditions may be treated through compaction grouting, granular soils, silts and some clays. It is critical that the grouting contractor pump at a relatively slow rate to allow dissipation of pore water in the surrounding soil, and to limit the ground's tendency to fracture. Pumping rates of 2 cubic feet per minute or less are generally acceptable. Grouting treatment of saturated highly plastic or organic soils (peat) may result in local soil *displacement*, however, little or no actual soil

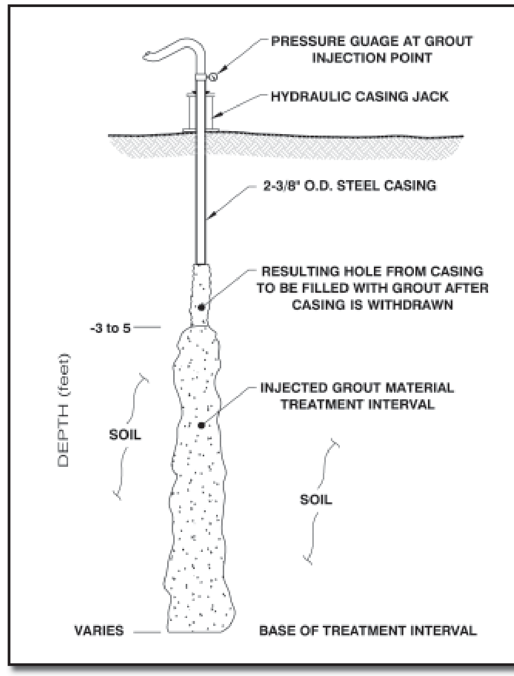

Figure 2: Generalized compaction grouting injection profile.

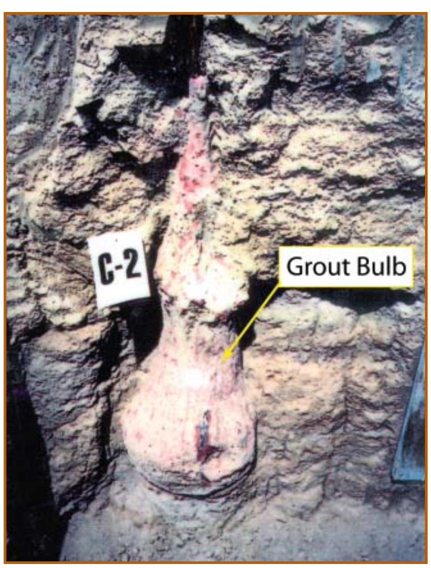

Figure 1: Grout bulb excavated during a 1991 study of compaction grout rheology. The study is documented in a paper by Warner, et. al. in ASCE's GSP No. 120.

Figure 3: Compaction grouting of an historic military barracks building in Hawaii at the edge of a dormant volcanic crater. The building was lifted off of the ground to provide construction access for various trades, but not a prerequisite for compaction grouting.

Figure 4: Grout injection for liquefaction mitigation beneath a smokestack at San Diego, California's historic Hotel del Coronado. Such limited-access project constraints are common in the compaction grouting industry.

improvement will likely be achieved. Site ground conditions should be well understood prior to beginning any production grouting program. Often times it is desirable to conduct a pilot grouting program as a means of gathering additional site performance data.

Grout Materials

In 1980, the Grouting Committee of the American Society of Civil Engineers (ASCE) defined the term "compaction grouting" as:

"Grout injected with less than one inch slump. Normally a soil cement with sufficient silt sizes to provide plasticity together with sufficient sand sizes to develop internal friction. The grout generally does not enter soil pores, but remains in a homogenous mass that gives controlled displacement to compact loose soils, gives controlled displacement for lifting of structures, or both."

For the purpose of this article, the term will include a broader-based class of limited-mobility displacement grouting, as this type of grout can be effectively emplaced at slightly higher slump values. A compaction grout mix is designed to be a blend that will flow in the injection pump and hoses, but resist the tendency to flow upon exiting the grout casing at the point of injection through loss of bleed water. It is typically a mixture of silty sand, eight to ten percent portland cement or fly ash, and sufficient water to develop the desired consistency. Compressive strength of the grout material is typically on the order of 150 to 300 psi, although adjustments in cement content, aggregate quality and use of additives can yield slightly stronger values. However, for most compaction grouting applications, grout compressive strength would only need to be equal or greater than the surrounding treated soil.

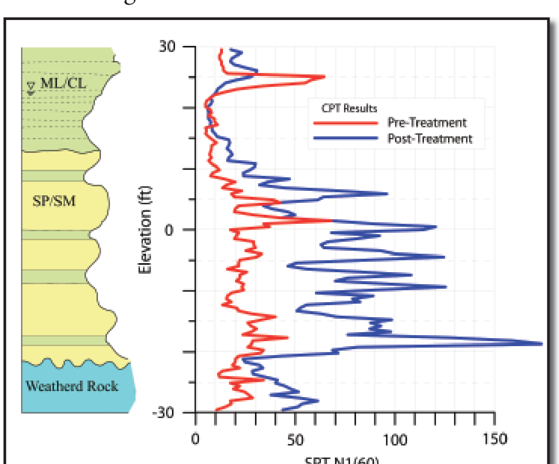

Figure 5: Comparison of pre- and post-treatment N1 (60) values from a residential liquefaction mitigation project in Laguna Beach, California. Soil improvement in the target treatment interval was considerable.

Classic Applications

Compaction grouting was recently used to address differential settlement potential beneath an important historical military site at Pearl Harbor, Hawaii. Reported by *Building Industry Hawaii* to be the first compaction grouting project done on the islands, this project involved grout treatment of differential fill beneath a barracks building, originally built in 1943 as part of the United States Navy Pacific Fleet Radio Unit. The barracks building had been constructed at the interior margin of Makalapa Crater, a dormant volcanic feature that had been partially filled with earth material.

Approximately 4,500 cubic feet of low-mobility sand/cement grout was used to strengthen the problematic soils. The project also involved replacement of the foundation system, and extensive interior and exterior renovations. Grout treatment was strictly used to strengthen the treated soil profile, as all grouting and foundation work was performed while the building was suspended in place (*Figure 3*).

Displacement grouting has been used to fill subsurface solution cavities or "dolines" at the University of California, Santa Cruz as a pre-construction site improvement measure. The process was recently performed at the campus to stabilize foundation subgrades for new construction, including the university's new science and engineering buildings, and a student housing structure.

Dolines are sinkholes that develop in areas underlain by limestone or marble bedrock, resulting from local chemical erosion. Surface water will pick up a small quantity of carbonic acid from the natural decay of organic matter. The water eventually percolates under-ground, allowing small quantities of this weak acid to slowly dissolve portions of the rock, usually along existing fractures or joints. Calcium carbonate is carried away in solution, leaving behind the insoluble portions of the rock. The result is a doline, typically filled with weak clay and silt — unsuitable for modern structural support.

Mitigation measures at the Santa Cruz, California campus involved drilling and grouting on a widely-spaced injection array. The geotechnical engineer was constantly on-hand to adjust the grout injection array to conform to empirical grouting performance data as the work progressed. Grout design considerations included a minimum strength criterion of 500 psi, and a zero- to one-inch slump. Fine aggregate for the grout mix design conformed to a specific gradation tolerance in order to limit the grout's mobility when pumped. This gradation is basically silty sand with between 10 and 30 percent passing the #200 sieve, and containing little or no clay.

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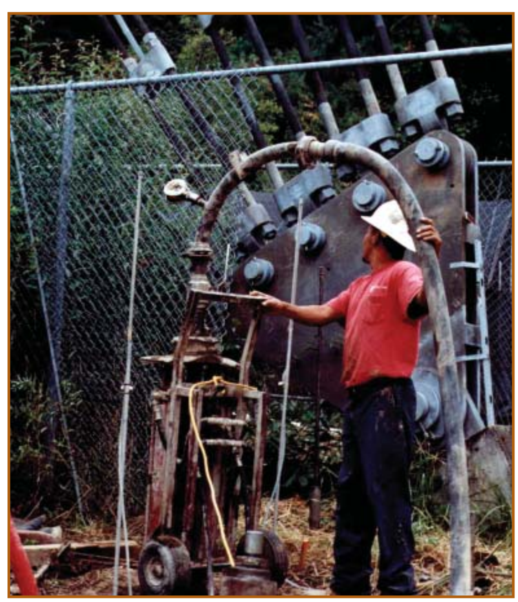

Figure 6: Grout injection being performed at one of the three anchor stanchions for a television broadcast tower.

The grouting process involved pumping through a small diameter steelcasing, initially set to the base of the solution cavity, and withdrawn in short intervals or "stages" as grout injection progressed. Grouting termination criteria were based on achievement of a maximum pressure, or a measured degree of ground uplift. A total of 31,500 cubic feet of grout was pumped at a total of 29 locations to stabilize the subgrade for the student housing building, and maximum treatment depth ranged from approximately 60 to 90 feet below the surface.

Compaction grouting is also routinely used to raise and relevel structures and foundation elements that have settled due to compression of supporting soils. This type of releveling requires a great deal of experience on the part of the practitioner, and careful monitoring of changes in relative floor elevation throughout the entire project. The degree of lift achieved depends on several factors, including treatment depth, grout consumption, the structure's response, and the client's objectives. Lifting structures with displacement grouting methods can have an advantage over conventional underpinning techniques, since grouting can actually address cause of settlement and provide support for slabs and other appurtenances.

Liquefaction Mitigation

Mitigation of liquefaction potential has become an important goal for many ground improvement projects. Compaction grouting techniques have been used in this capacity at many locations, including the Monterey Bay Aquarium Research Institute in Moss Landing, California; a portion of the historic Hotel Del Coronado in San Diego, California (*Figure 4*), and as part of a retro-fit of a former Montgomery Wards building for a new Target retail center, also in San Diego. This was one of the largest projects of its kind, involving injection of 165,000 cubic feet of low-mobility grout at 2,762 injection points.

Compaction grouting treatment for liquefaction mitigation was recently conducted for a proposed residential site in Laguna Beach, California to densify sandy alluvial soils. Project planning called for a new home to be built on a lot where the engineer had identified a potential liquefaction hazard. Site stratigraphy consisted of approximately 20 feet of thinly-bedded soft to medium-stiff silts and clays, overlying loose to medium-dense sandy alluvium. A sharp near-horizontal contact with local conglomeratic bedrock was encountered at approximately 60 feet below the ground surface (BGS). Ground improvement was primarily directed at treating saturated granular alluvium.

Plan-view grout injection point spacing of 8-feet on-center was selected for the Laguna Beach project, based on results of a preliminary test program. The graph in *Figure 5* shows considerable improvement in SPT N1 (60) values, as determined through cone penetrometer (CPT) testing. Results were compiled from two pre-treatment soundings, and seven post-treatment tests. A total of about 22,000 cubic feet of grout was emplaced at this site, with an equivalent displacement ratio of 5.6 percent.

Soil Stiffening

Compaction grouting was used to strengthen the soil reaction zone of a failing anchor structure for a television broadcast tower near Portland, Oregon. An unusual wind storm with sustained gusts of up to 50 mph had induced random motions in the supporting cables for the 1,100-foot high, 680 ton broadcast tower. Observed amplitudes in the 2-inch diameter support cables were on the order of 20 feet. Subsequent geotechnical studies revealed that two of the tower's anchors were failing with respect to uplift.

Compaction grouting and a series of micropiles were applied as a remedial construction measure to stabilize the anchors prior to re-tensioning of the support cables. Each anchor had to be able to comfortably resist approximately 300 tons of uplift. Subsequent monitoring of the structure's instrumentation has demonstrated that tower and anchor motions are within expected parameters. The accompanying photo (*Figure 6*) shows grout being injected near one of the tower's anchor stanchions to stiffen soils in the foundation reaction zone.

Figure 7: Stiffening of the supporting soils for the lower tier of this retaining wall was accomplished by carefully-controlled and closely-spaced compaction grout injection. Grouting in this case was performed in preparation for a series of tieback anchors that were installed once grouting was complete.

Another unusual structure to benefit from compaction grouting included a failing earth-retaining wall in Orange County, California (*Figure 7*). Compaction grouting was performed in the supporting soils beneath and behind the lower-tier wall to address weakened backfill, and to stiffen the inbound reaction zone for a series of tieback anchors that were ultimately installed. Careful monitoring of injected grout quantities, surface uplift and wall deflection were critical to this project's success.

Compensation for Soil Piping

Displacement grouting was used to repair a breach beneath a seawall and revetment during construction of the Ocean Institute's new Ocean Education Center at Dana Point Harbor, California. The harbor had locally breached a 16-foot deep construction excavation during a high-tide event, and grouting was used to restore revetment

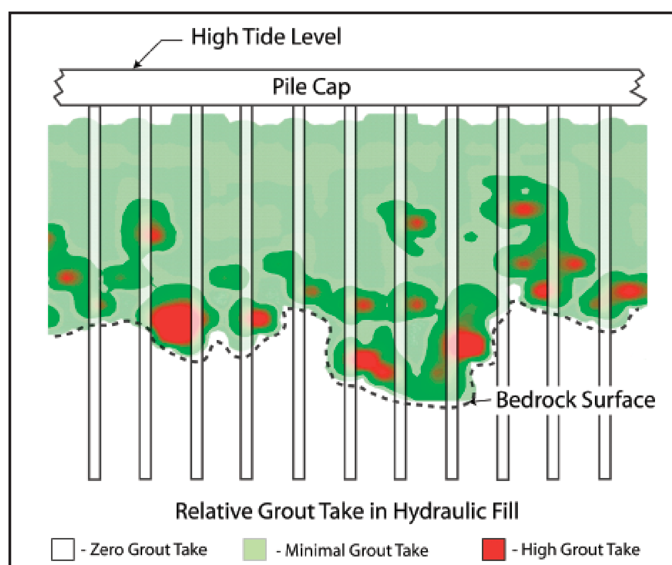

Figure 8: Grout consumption at each injection stage was contoured to produce this diagram. Soil piping along the basal bedrock surface hastened local soil loss in overlying intervals, and is reflected in the sporadic relative "takes" in the hydraulic fill.

support once the breach was sealed. Local piping of fill soils along a basal bedrock surface contributed to a weakened condition in the area of the breach, and grouting was performed along the remainder of the seawall to identify and "heal" other potential zones of soil loss. A grout mix with a slump of approximately 6 inches was used for this application, allowing the grout to travel slightly farther from the point of injection.

Figure 9: Computer technology is becoming more common in the grouting industry. The manifold shown above contains a pressure transducer and wireless transmitter that works in conjunction with an in-line flow meter. This configuration allows real-time monitoring of pressure and flow for very stiff (zero-slump) grout mixtures.

Figure 8 depicts anomalous zones of relatively high grout consumption, in profile view. It is believed that those zones represent areas of "chimney effect" soil loss resulting from piping. This early stage of sinkhole formation was effectively healed through the displacement grouting process. This is also an example of how grouting can be used as an effective diagnostic tool.

Reporting and Monitoring

Compaction grouting results are carefully recorded in the field by the foreman or responsible technician. Records of casing installation and grout consumption per stage are maintained, as well as injection pressure and production rate data. The degree to which the ground accepted grout treatment is typically expressed as a volumetric displacement ratio of grout injected to soil treated; either based on a hypothetical radius of influence surrounding each injection point, or by considering the total area treated.

Although compaction grouting is typically considered to be a "low-tech" process, its application has begun to benefit from many of the "high-tech" gadgets that are becoming available. The use of computers has given the industry a means of measuring grout flow, pressure and consumption in real time, allowing engineers and practitioners to identify ground shears in the very early stages. The in-line flow meter and pressure transducer shown in *Figure 9* provides metering of very-stiff grout mixes with wireless telemetry.

Simple manometer surveys are nearly always used to quantify pre- and post-grouting changes in relative floor elevation, although laser scanners have great potential as a means of documenting minute structural deformations with little added expense. There are also many types of automatic devices that can be applied to measure surface heave or movement of critical structures, including tiltmeters, electronic manometers, and autonomous "total station" arrays. However, conventional manometers and optical levels are considered sufficient effort for most applications and project budgets.▪

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Resources

Although this article is intended as a "broad-brush" overview of the subject, there are many grouting-related resources available for design professionals, both in print and on the internet. One of the most recent publications to compile a comprehensive body of knowledge on the subject is a text by James Warner, titled *Practical Handbook of Grouting: Soil, Rock and Structures*, published by John Wiley & Sons, Inc., 2004. Many other publications and proceedings are also available from the ASCE Bookstore and other publishers. The Geo-Institute Grouting Committee's website is another good resource for grouting information, and can be found at: **www.grouters.org**. The committee will soon be releasing an updated Glossary of Grouting Terms, and a set of Compaction Grouting Guidelines.▪