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Soil Improvement to Mitigate Settlements under Existing Structures

H. R. Al-Alusi,[1] Member, ASCE

ABSTRACT: Settlements of sites with existing structures are more difficult to mitigate than those of sites without structures. Equipment access, work area, noise, dust, vibrations, and cost are amplified and become more critical.

Following are three case histories involving mitigation of settlements under three different types of structures.

The first case, an office building in the San Francisco Bay Area, involved soil densification under piles to mitigate further settlements. The compaction grout densification process was extended beyond the bottoms of the piles to treat fill materials under the footprint of the building. Additional lense grout reinforcement was required to reinforce the hillside soils to reduce downward movements. Five years after completion of remediation work, the site showed no detectable movement.

The second case concerned a maintenance facility at the June Lakes Ski Resort in the Sierra Mountains, where a structure had been built on top of a fill that was underlain by a layer of gravel and cobbles. Within a year of construction, signs of structural distress were evident. Geotechnical investigations revealed that settlements were caused by at least two factors; the downward migration of the upper fill layer into the large pores of the lower layer, and the possible densification of the upper fill under its own weight. The remedial work consisted of providing a barrier between the two layers to allow for an effective compaction grout densification effort of the upper fill layer and to prevent further migrations into the

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[1] President, Pressure Grout Co., 1975 National Avenue, Hayward, CA 94545-1709.

gravel and cobbles layer. No structural distress or any movement has been detected since the remedial work was completed six years ago.

The third case presents the treatment of the old and new footings of the Rose Bowl Stadium in Southern California. A permeation grouting system was selected, designed, and implemented to solidify zones of the sand-gravel-cobbles mixture of the foundation soils to act as pedestals for underpinning the old footings and supporting the new ones.

INTRODUCTION

Settlement of structures can be caused by a number of factors. These factors include the settlement of the soil caused by its own weight, loads applied by and through the structure, vibrations, change in groundwater levels or other less known factors such as plant root moisture extraction, erosion of a soil layer into a coarser particle layer, chemical reactions, thermal exchange, mineral dissolution, underground erosion due to migration of smaller soil particles caused by groundwater gradients, and many others.

Loads applied by and through a structure may include its own dead load, live loads, wind, seismic, impact and other functional loads. A frequently encountered settlement problem is the inadequacy of soil density/strength resulting in soils consolidating or compacting under their own weight. A soil improvement can be affected by simply densifying the soil mass in-situ without removing the soil or affecting the structure.

Mitigation of soil settlement under existing structures by in-situ pseudo-static densification has been used for more than forty years in the U.S.A. These solutions are achieved by compaction grouting (further detailed in case history No. 1). Other lesser known methods include soil solidification, soil reinforcement, soil sealing, and other methods of soil treatment. Each one of these approaches has several critical details that demand the engineer's and contractor's full attention to achieve successful completion. The three cases presented in this paper represent soil improvements to mitigate settlements caused by several factors. Each case involves an existing structure where on-going settlements needed to be halted.

CASE NO. 1

A two-story office building, measuring 24.4 x 76.3 meters, exhibited continuous settlements within five years of construction completion. When the differential settlement reached 100 mm it became evident that a remedial work program was necessary.

The site was resting on a two-stage graded fill (Fig. 1). Fill thicknesses (wedges) of less than 1.5 meters and up to 6.1 meters underlaid the footprint of the subject structure. Upon completion of construction the longest side of the building was parallel to a heavily vegetated slope of about 1:1, with a height of 4.8 to 6.1 meters. The building was resting on drilled piles of varying depths from 2.8 to 4.9

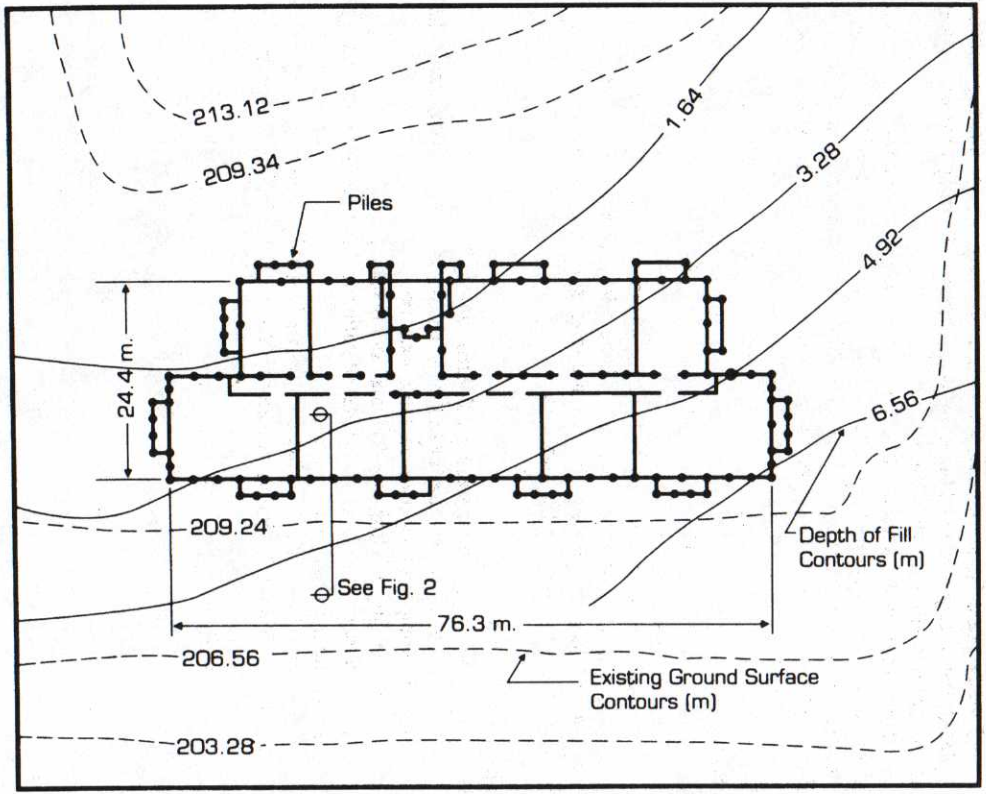

FIG. 1. Building Plan and Contours

meters and with diameters of 0.46 to 0.61 meters. The piles were connected by grade beams, with the floor slabs doweled to the beams.

Twenty years before completion of the building, rough grading had been completed; the final grading and building construction were completed about twelve years before this remedial work started.

Settlement monuments on the grade beams showed a maximum differential settlement of 100 mm across the building, (Fig. 1). Observation of the soil surface in comparison to the grade beam showed a difference of an additional 200 mm of soil movement downward relative to the grade beams. Slabs were exhibiting sagging of up to 70 mm between the grade beams.

Continuous monitoring showed that there were two types of movement. The first was downward, which was attributed to the compaction and consolidation of the fill and native soils. This movement was detected by settlement monuments and the generation of voids below slabs. The second was a hillside creep movement caused by the seasonal drying and wetting of the near surface soils of the slope. A typical soil profile of this site is shown in Fig. 2. The pile settlements were attributed to the additional loading imposed by the negative skin friction generated by the downward movement of the fill materials.

Approach Concept

A number of solutions were considered, among them were:

a. Removal and preservation of building, excavating and re-compacting soils, and resetting building back on same location.

b. Re-supporting building on additional and deeper piles.

c. Improvement of soils by in-situ densification and mitigation of downhill soil movement, by soil reinforcement.

Solution (a) was quickly discarded because of its prohibitive cost and time requirements. Solution (b) was estimated to be many times higher in cost and time requirements than Solution (c).

The remedial work consisted of two major items, namely:

1. Densification of soils below the bottom of the piles and under the rest of the building using compaction grouting, and

2. In-situ soil reinforcement using deep lense grouting under the hillside area.

Fig. 2 represents a conceptual sketch of the remedial work undertaken for this building.

Compaction grouting is the injection of a highly viscous sand-cement mixture designed to volumetrically displace and densify the soils around the point of injection. Compaction grout by definition (Committee on Grouting 1980) is a grout with 50 mm or less slump per ASTM C143-78. Grout materials, pressures and rate of injection were designed to prevent the permeation of the grout into the soil mass and to prevent the fracturing of the soil itself. The strength of the grout material is irrelevant in the compaction grouting process. The amount of densification and the extent of the densification process are the crucial elements in this operation.

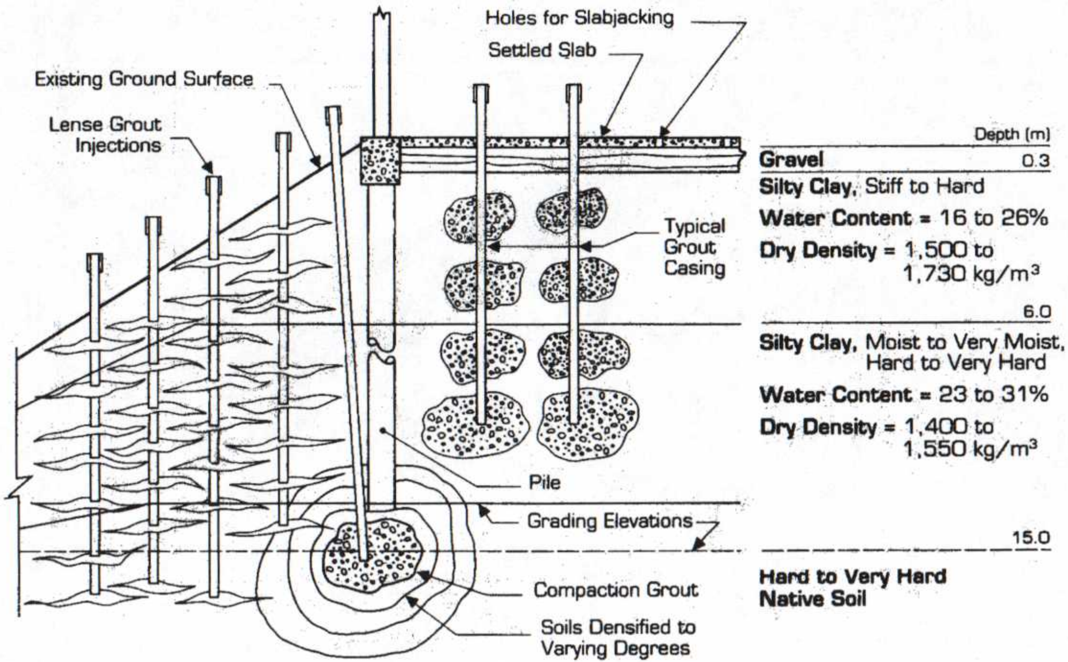

FIG. 2. Cross-Section through Building Foundation and Slope Area (for Location See Fig. 1)

Soils closest to the grout bulb will exhibit highest densification with a diminishing effect away from the point of injection.

Compaction Grout Materials

Materials used in compaction grouting have a wide range of properties. Theoretically, any material that will not permeate, spread, or fracture the soil when injected is an acceptable material. For cost considerations, local materials for a given project site are usually given first priority. Additives can be used to improve the grout material pumpability. As an additive, portland cement is widely used with sufficient water to effect a workable mix. The use of cement is strictly for the workability and pumpability of the material and does not affect the required degree of densification. Compaction grout materials with no cement content or other additives have been reported (Stoker and Wardwell 1987). A set of particle size distributions of materials used in compaction grouting, compiled by the author, is given in Fig. 3. A cement content of five to fifteen percent has been used with these materials.

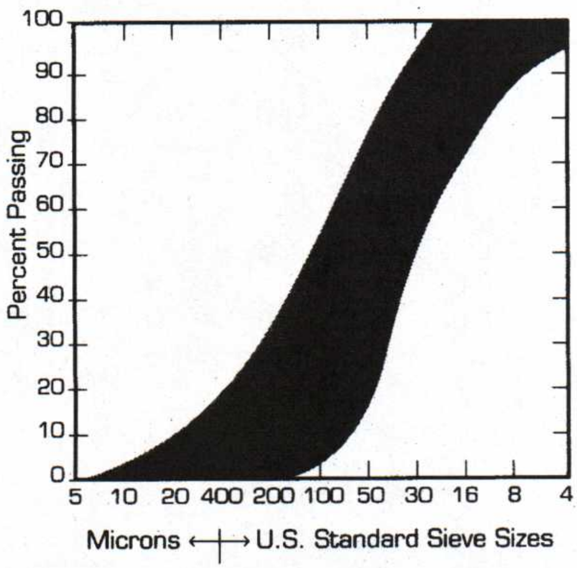

FIG. 3. Gradation for Sand Materials for Compaction Grouting

Soil Densification

The remedial work included only a portion of the building as seen in Fig. 2 This portion represents approximately two-thirds of the total area of the building.

Based on the available settlement records, 63 piles were found to be in need of re-support. A single injection point was used for each pile. Injection points were designed so that the tip of each grout casing was between the center of the pile bottom and the top of the competent soil layer. At each injection point grouting continued until pile upheave or a maximum grout pressure of 4100 kPa at the point of injection was detected.

The aim of this portion of the treatment was to create a grout bulb (footing) as large as possible under the pile until refusal criteria, as given above, were met. The grout take was largely dependent upon the consistency of the material below the bottom of the pile and the distance between it and the competent soil layer below it. Grout takes ranged between 0.17 to 4.73 cubic meters with an effective spherical bulb diameter of 0.67 to 2.11 meters.

For the remaining soil mass (Fig. 2), a grid pattern with a spacing of 1.83 x 1.83 meters was established. The sequence of injections was designed to first create a confinement of the soil mass to be densified, then to proceed with the remaining densification process. Each injection point was driven to the target depth. Grout extrusion started in stages of 0.61 meters in the vertical direction without stopping until a maximum pressure of 4100 kPa was reached or a ground upheave was detected. A total grout take of five to seven percent of the volume of the treated soil was accomplished resulting in four to eight percent increase of the soil dry density.

Soil Reinforcement

The deep soil reinforcement included injections of grout lenses to a maximum depth of 11 meters. Lenses were installed at 0. 31 meters intervals vertically. Each lense was designed to fracture the soil and install grout to create a lense of 3 meters in diameter with a thickness of 3 to 6 mm. Injections were installed in a grid of 1.83 x 1.83 meters, Fig. 2. The over-lapping of these lenses provided a continuation of the reinforcement to resist the small but on-going creep movement. A slurry grout mix of a water/cement of 2 was used together with additives, as needed, to provide for the pumpability of grout and to facilitate fracture initiation.

The mechanism of soil reinforcement is based on the friction/bond between hardened grout lense and the soil, much the same as metal strips in reinforced earth applications (Tabbal 1983).

Performance

No detectable settlements have been observed in the four years since completion of the work.

The hillside showed minor movement for a few months after work completion, but even those movements were greatly reduced to hardly detectable amounts since then.

CASE NO. 2

This case presents remediation of a condition of downward migration of a finer grained fill soil into a layer of gravel and cobbles. A concrete-block building of 18.3 x 39.7 meters with a slab-on-grade floor was constructed in 1986. A cut-fill approach was used to create the original level pad. The gravel and cobble layer was covered with additional fill of silty sand 4.58 meters thick, Fig. 4. Within a year after construction of this building, cracks in the walls and the concrete slab appeared. A maximum differential settlement of more than 76 mm across the building was measured before the initiation of the remedial work. A trench excavated adjacent to one of the footings, just before undertaking the remedial work, revealed a substantial void between the bottom of the footing and the soils below it. Four borings drilled around the building showed evidence of extensive intrusion of the silty sand layer into the gravel and cobble layer.

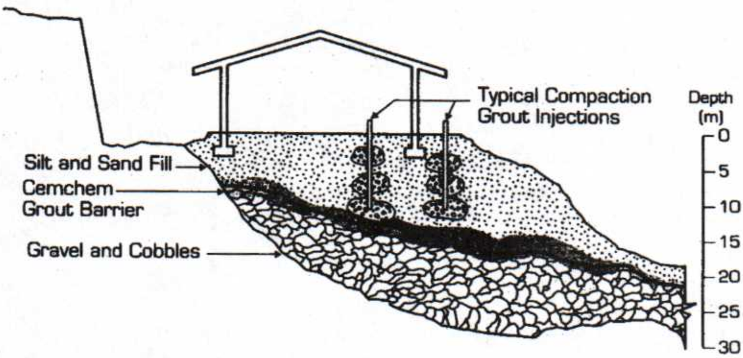

FIG. 4. Section through Foundation Soils Showing Remedial Work

Approach Concept

The lateral and vertical extension of the gravel and cobbles zone, coupled with its very high permeability, necessitated the installation of a grout blanket (barrier) just under the silty sand fill to block the silt and sand intrusion into the gravel and cobbles layer. Cemchem, a controlled fast-gel grout, was selected for this situation. This proprietary system can be controlled to set between twenty seconds and one hour after mixing. With proper mix design, length of grout pipe, depth of soils to be injected and equipment arrangement, the grout can be designed to set within a few seconds after it leaves the tip of the grout pipe.

The remedial work consisted of installing this barrier, then densifying the soils above it using compaction grouting. This was followed by void filling, and structural lifting using compaction grouting techniques to lift and level the structure and slabs.

Remedial Work

Using CemChem grout a blanket with a nominal thickness of 0.3 to 0.6 meters was established in the areas that needed it. By probing in a grid of 0.92 x 1.22 meters, it was first determined whether or not the sand intrusion had reached a point where it had already established a barrier. If the grout permeated the soil, it was assumed that a barrier had not yet been created. If, on the other hand, it did not permeate the soil, the assumption was that the sand had already created a barrier within the gravel and cobble layer, thus no further work would be required in the vicinity of that injection point. The establishment of the blanket required more than 30,300 liters of CemChem grout. This procedure was then followed by compaction grouting to densify the loose soils above the barrier. A grid of 3.66 x 4.27 meters for casing injections was first driven and pumped, followed by splitting this spacing into 1.83 x 2.14 meters. Total compaction grout injected was about 140 cubic meters, which resulted in an improvement of the bulk density of the treated soils of between 15 and 21 percent. The compaction grout was injected in stages of 0.3 to 0.6 meters starting at the top of the blanket and moving upwards to the bottom of the floor slabs or footings. Grout injections were terminated when the grout pressure reached 3445 kPa or the surface lifted to an unacceptable level.

Grout Materials

For the CemChem system, portland cement is the base material. Portland cement Types I, II or V have been successfully used together with bentonite and additives to produce the required gel time.

For the compaction grouting, locally available silty sand was used. This material was found to satisfy the criteria given in Fig. 3. Portland cement was added at the rate of ten percent by weight of grout.

Performance

More than six years after undertaking this remedial action, no distress or movement has been reported.

CASE NO. 3

Loose to medium granular soils undergo volumetric changes (settlements) under additionally imposed loads, vibrations, and seismic activities. If such soils contain larger particles of gravel and boulders in a heterogeneous formation, settlement predictions become highly complicated.

This case history involves the 1915 Rose Bowl Stadium in Southern California (listed as a historical monument). The stadium was undergoing an expansion project involving the press box and new executive suites which resulted in additional loading on the footings. Portions of the new expansion would be supported by some of the old stadium footings and others by the new footings. It was determined that the old footings themselves rested on loose uncompacted fill, making it impossible to underpin the old stadium footings without damage to the structure unless and until the soils below these footings were given additional support.

Approach Concept, Remedial Work and Materials

The solution to this condition was through a permanent solidification system using permeation grouting with chemicals. Injections designed to create "solidified pedestals" of about 1.22 meters in diameter were used. For permanency, strength, and environmental considerations, an ultrafine cement grout was selected. Before finalizing the designs, a pilot test program was undertaken at the subject side . The results revealed satisfactory grout permeation into the soils with an unconfined compressive strength exceeding 1380 kPa. The geotechnical design proceeded with 1,000 pedestals (injections) under the old and new footings.

The site soils immediately below the footings had a gradation that ranged between silt particles and cobbles. Less than five percent of the particles passed the 200 U.S. Standard Sieve (0.075 mm) while the largest particles were up to 100 mm. In ultrafine cement more than 80 percent of its particles are smaller than 6 microns. A water/cement ratio of 4:1 was used. Each injection required 170.5 liters. Nominal pressure used for these injections was 345 kPa.

Performance

The program proved to be successful in terms of being able to affect the required solidification. More than a year has passed since the completion of this work. Full loads have been imposed with no signs of any settlement. It is fair to assume that the designs and remedial work will perform successfully based on the excellent grout take that was recorded at the site and the strength of the obtained samples.

CONCLUSION

Mitigation of settlements of existing structures involves stringent requirements to satisfy the site, soil, and structural specifics. The three case histories presented in this paper show how such specialized methods can be used to halt the settlement of structures in a cost-effective way. Replacing structures, re-excavating or re-supporting existing structures on piles are not the only solutions available to the geotechnical engineer today.

APPENDIX - REFERENCES

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