Control of Soil Improvement by Crosshole Testing

Crosshole pour Vérifier Sols après Injection

R.D. WOODS Professor of Civil Engineering, University of Michigan, Ann Arbor, Michigan, USA
A. PARTOS Vice President, Site Engineers Division, Day & Zimmermann, Inc., Philadelphia, Pennsylvania

SYNOPSIS It was desired to convert an existing building from a light industrial use to an application requiring die forging machines. The soils at the site consisted of loose, silty, fine sands to a depth of about 16 m. Compaction and chemical grouting were proposed to improve the site. Resonant column tests were run on compacted and chemically grouted samples of the sand to find the range of achievable shear moduli. Crosshole seismic tests after each of two stages of compaction grouting and after chemical grouting provided a very sensitive and accurate method of checking soil improvement. Vibration measurements after 2 and 14 months showed machine and floor motions in the expected range and no adverse settlements had occurred.

INTRODUCTION

A leading U.S. automotive tool manufacturing firm had an opportunity to relocate part of its die forging operations to an existing, attractive, vacant, light industrial building. During a pre-purchase inspection of the building by the junior author, it was learned that the soil at the site consisted of loose beach sand. This discovery was important to the decision to purchase or not, so borings were made in an area of the building where the die forges would be located. Two of those borings are summarized in the composite profile, Fig. 1, and are identified as B1 and B3 in Fig. 2, site plan. The second stratum of very loose, silty, fine sand with standard blow counts (N) as low as 2 presented a serious problem because it occurred at the likely depth of forge foundations, 3 m, and because compaction of the loose sand by forging generated vibrations could cause settlement of shallow column footings and the floor slab.

To improve the stability of the loose sand insitu, several techniques were considered, but most had to be rejected either because they were inappropriate after building construction or because they would generate potentially damaging vibrations. Based on the site inspection of the structure and subsurface conditions by the junior author, it was concluded that grouting the loose sand, subject to careful field control, was the most feasible approach to site improvement.

GROUTING PROGRAM

To reduce the potential for settlement due to compaction of the loose sand by forging vibrations and to provide an adequate base for the die forge foundations, the loose

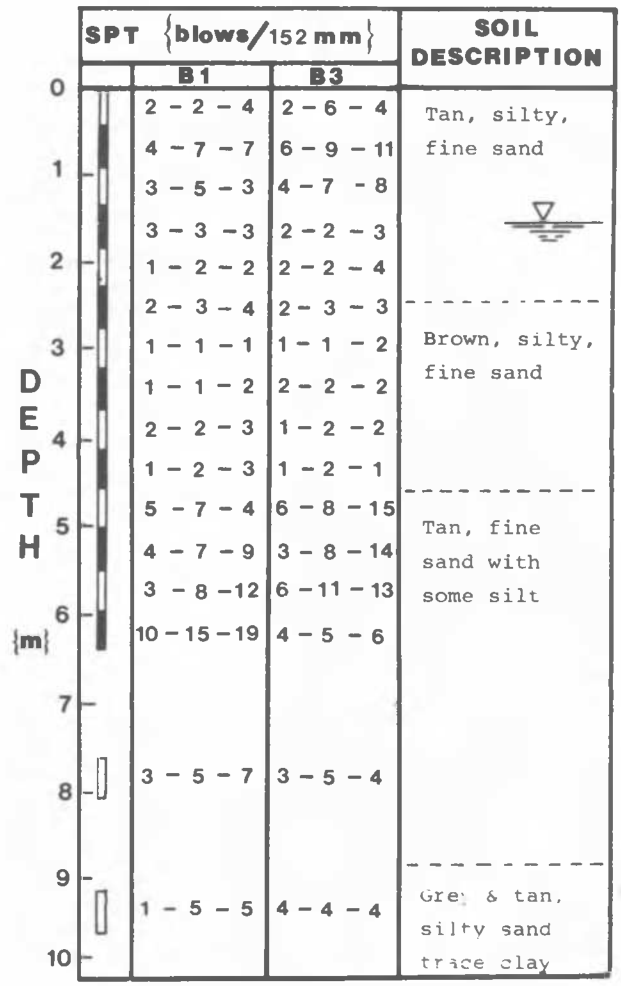

FIG. 1 - COMPOSITE SOIL PROFILE

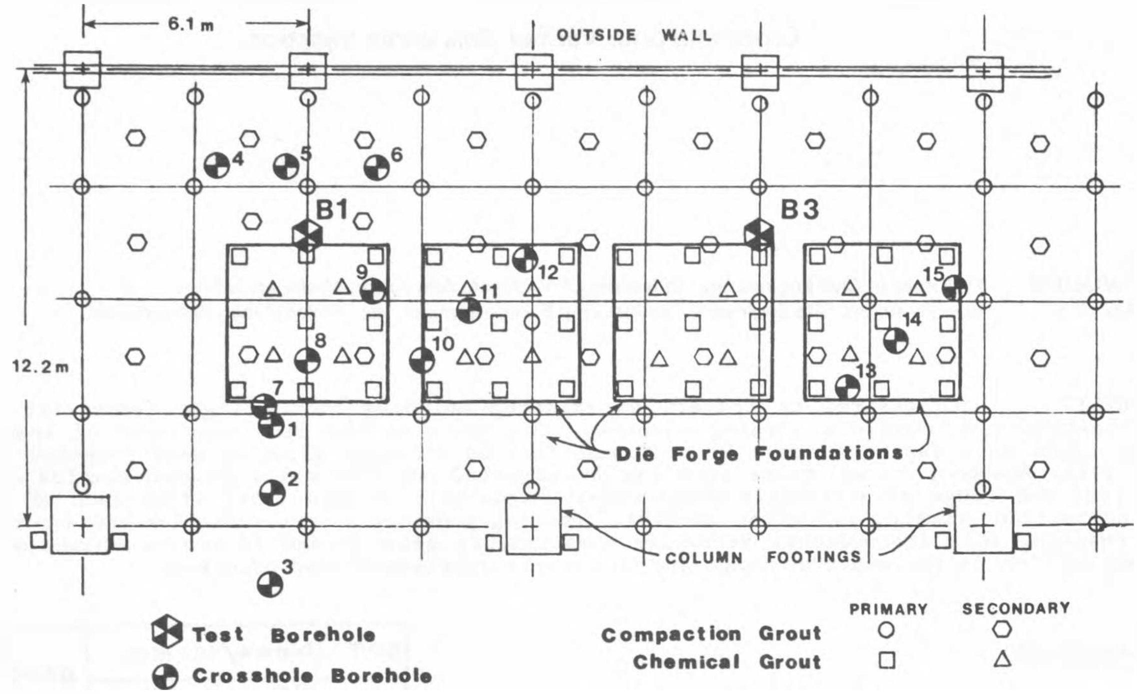

FIG. 2 - SITE PLAN

sand had to be stabilized. Grouting technology provides two approaches for stabilizing the sand: reduce the void volume by compaction grouting, and/or fill the void space and solidify the mass by chemical grouting.

Economics of both grouting techniques depend upon the volume of soil which must be treated. Through mutual consultation, the industrial designer and the authors selected a layout, Fig. 2, which provided economy in the grouting program and sufficient isolation for vibrations and suited the manufacturing process. This region consisted of an area of about 300 m^2 which amounted to about 6% of the building area. The depth of soil treatment based on the soil profile was selected to extend to about 10 meters.

Warner and Brown (1974) presented an equation relating grout take to density improvement for uniform, well known soil profiles. Because of the variable densities at this site, advice was sought on an expected degree of improvement from a soil modification specialist. His estimate was that the maximum relative density that could be achieved by compaction grouting at this site would not exceed 75%. Because a relative density of 75% represents a borderline condition with respect to vibratory settlement, additional stabilization was sought through the use of chemical grout. However, as pointed out by Karol (1969), chemical grouting must be carefully considered and sparingly used because of the higher cost of the grouting materials and injection process.

A general grouting plan was formulated using compaction grouting in a broad area surrounding the locations of the forge foundations and chemical grouting directly under the die forge foundations and under nearby column footings. Both types of grouting operations were planned to be executed in two stages, the first stage on a wide spaced pattern and a second stage at intermediate locations. Figure 2 shows locations for both stages of compaction and chemical grouting. Symbols for each stage are identified in the legend of Fig. 2. It was anticipated that in some areas only one stage of grouting might be required, however all grout locations were eventually used.

The chemical grouting phase of the program accomplished supplementary goals, those of permitting the excavation for the forge foundations to be made in the dry 2 m below groundwater without de-watering or sheeting, and permitted casting the foundation block in contact with the surrounding soil to take maximum advantage of foundation embedment in reducing dynamic response. The chemical grouting was so effective that some of the grouted soil had to be removed with an air hammer.

The dynamic response of the die forge-foundation-soil system was analyzed by the analog half-space procedure described by Richart, Hall and Woods (1970). It was determined that satisfactory dynamic response of the 290 kN forge and foundation system could be realized if the shear wave velocity for the first 3 meters under the die forger was 190 m/s or more, i.e. minimum shear modulus of 69 MN/m^2.

Having proposed a potentially useful soil improvement plan and a minimum soil condition to meet dynamic requirements, it remained to be shown that the grouting technique could sufficiently improve the loose sand to satisfy the requirements. A method for quality control was also needed to check grouting results in the field. Resonant column tests were performed in the laboratory to satisfy the first uncertainty and crosshole tests were selected to judge the degree of soil improvement in the field.

RESONANT COLUMN TESTS

Two sets of low amplitude resonant column tests were performed in a "fixed-free" apparatus using procedures reported by Afifi and Woods (1971). For one set of tests, samples from a depth of about 4.2 m were reconstituted to a relative density of about 75% to simulate compaction grouting and tested at average effective stresses of 27.6 kN/m^2 and 69 kN/m^2. Shear wave velocity vs. time after confinement data for those tests are presented in the lower portion of Fig. 3. At 27.6 kN/m^2, the controlling pressure used in the dynamic response analysis, the desired 190 m/s shear wave velocity was not achieved. At 69 kN/m^2 confinement, approximating conditions at the bottom of the grouted zone, the minimum required shear wave velocity was exceeded.

The second set of resonant column specimens were prepared by the grouting contractor by injecting chemical grout (GELOC-3) into loose sand samples at a relative density of about 45%. GELOC-3 is a sodium silicate type grout composed of about 40% liquid sodium silicate, 5% to 10% organic solvents and salts, and the balance water. These specimens were hand delivered to the laboratory and tested within 4 days of preparation at confining pressures of 27.6 kN/m^2 and 69 kN/m^2. Results of these test are plotted in the upper part of Fig. 3. Under both confining pressures shear wave velocities substantially exceed 190 m/s.

It was concluded that chemical grouting alone or in combination with compaction grouting would achieve the goal. On this basis, the vacant property was acquired.

CROSSHOLE TESTS

It was recognized that neither compaction nor chemical grouting would produce a homogeneous mass of stabilized sand. Consequently an "average" or "effective" shear wave velocity should be sought in judging the effectiveness of the grouting program. The seismic crosshole technique is ideally suited for measuring average shear wave velocity through soil and was selected for quality control during the grouting program.

The multiple borehole crosshole method described by Woods (1978) was used to measure shear wave velocity as a function of depth at 5 locations in the treatment area shown in Fig. 2. Three boreholes were required at each test location and these boreholes were lined with PCV casing grouted in place. The same boreholes were preserved and used after each stage of grouting.

Crosshole tests performed at boreholes 10-11-12 and 13-14-15 after first stage compaction grouting resulted in shear wave velo-

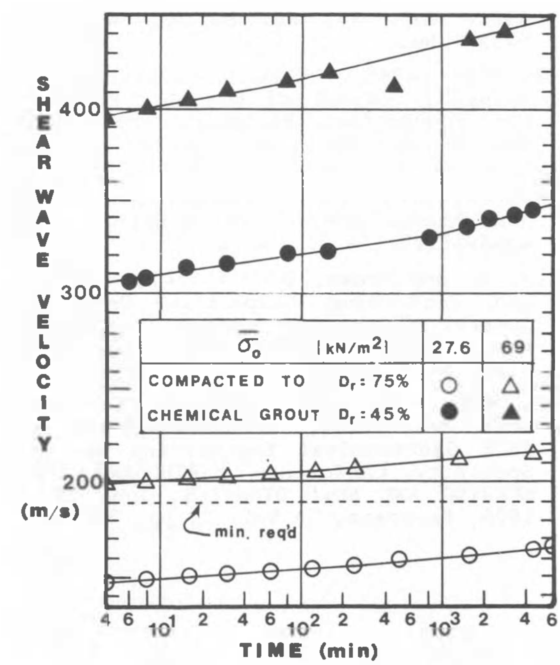

FIG. 3 - SHEAR WAVE VELOCITY VS. TIME

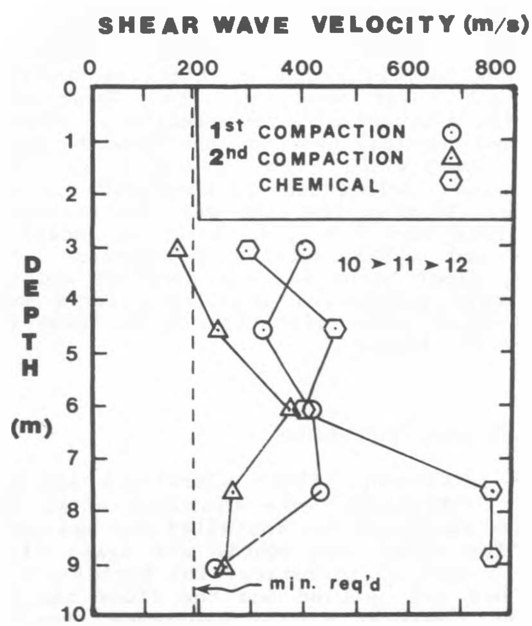

FIG. 4 - SHEAR WAVE VELOCITY PROFILE

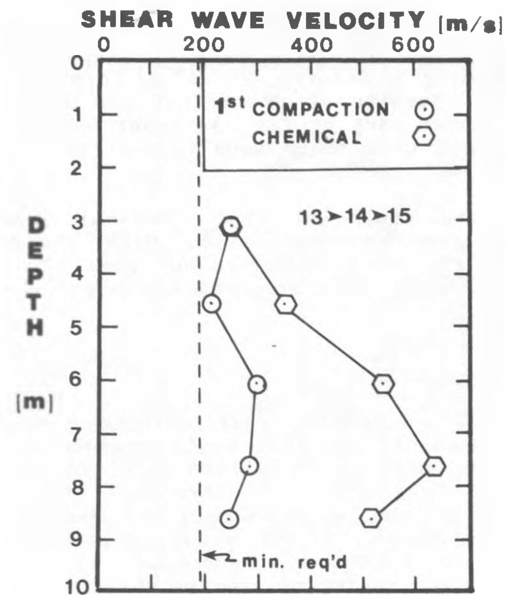

FIG. 5 - SHEAR WAVE VELOCITY PROFILE

city vs. depth profiles as shown in Figs. 4 and 5 (circle symbols). Shear wave velocities exceeded the 190 m/s criterion substantially at locations 10-11-12 but only slightly at location 13-14-15. Second stage compaction grouting was performed at location 10-11-12 and produced startling results. The triangle symbols on Fig. 4 show that the shear wave velocities decreased after second stage compaction grouting. It was observed during second stage compaction grouting that the floor slab was raised more than 25 mm in some places, and based on this observation it is postulated that horizontal stresses "locked-in" in the first stage compaction grouting were partially relieved by the "heaving" during second stage compaction grouting thereby reducing effective confinement and shear wave velocity. Shear wave velocity measured after completion of compaction and chemical grouting are shown by hexagonal symbols in Figs. 4 and 5 and show shear wave velocities substantially in excess of 190 m/s. The same was true at crosshole locations 7-8-9. At borehole locations 1-2-3 and 4-5-6 outside foundation locations, floor heave was not detected and the two stage compaction grouting program produced shear wave velocities of at least 190 m/s at all depths.

SUMMARY AND CONCLUSIONS

Floor settlement, floor vibrations and die forger vibrations were measured after the forging equipment was installed and had operated for about two months and again after about 1 year of operation. The building columns had not settled and the floor had not settled. Maximum single amplitude particle displacements (vertical) on the forge foundations were about 0.25mm at 20 Hz and on the floor at the edge of the grouted area were about 0.08 mm`also at 20 Hz. The vibration levels are below the limits for forging type operations. The combination of areawide compaction grouting and localized chemical grouting stabilized a loose soil under an existing building making possible the installation and satisfactory operation of die forging equipment. Key aspects of the success of this soil stabilization program were the resonant column tests to evaluate the feasibility of the grouting program and crosshole tests for quality control during the grouting program. The crosshole test proved to be a very sensitive and accurate technique for evaluating changes in soil stiffness due to changes in confinement, void ratio or particle cementing when waves were propagated over identical paths.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. J. Renninger of K-D Tool Co., Lancaster, Pennsylvania for permission to publish this study. We are also grateful to the late William F. Lotz, Jr. and Mr. G.K. Smith of William R. Lotz, Inc. for their encouragement of this work. Finally, we thank J.P. Welsh of the Hayward Baker Company for help in planning the grouting program and preparation of grouted specimens.

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