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General Report Session No. 7: Case Histories of Soil Improvement, Grouting, Geosynthetics, Dynamic Compaction, Vibroflotation, Blasting, and Other Methods

Donald Anderson
USA

B. G. Rao
India

S. Yasuda
Japan

R. Jewell
Belgium

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INTRODUCTION

Thirty papers involving the general area of soil improvement were assigned to Session VII, making this session one of the most published sessions in the Conference. Examples of case histories in the area of soil improvement came from all over the world, including Canada (2[1]), China (6), Croatia (1), India (5), Italy (1), Japan (2), Korea (1), Malaysia (1), Thailand (1), United States (9), and Venezuela (1).

While some of the authors describe soil improvement studies carried out to avoid risks from natural hazards such as earthquake-induced liquefaction, most of the authors report on improvement of soil (or ground) necessary to develop marginal soil sites. A decade or two ago these sites would have been bypassed in the development process, but now as "good" sites are becoming fewer and fewer, these marginal sites are being developed. Soil improvement technologies have offered the opportunity to use this marginal land.

As demonstrated by the contributions to this session, various methods of improvement are available. These methods range from the use of prefabricated vertical drains (wicks) and preloads to dynamic compaction. They are used to reduce settlement, increase bearing capacity, improve slope stability, or reduce liquefaction potential during seismic events. Various methods of soil testing are used to validate the improvement, including standard penetration tests (SPT), cone penetration tests (CPT), Becker hammer tests (BHT), vane shear tests (VST), pressuremeter tests (PMT), and dilatometer tests (DMT).

One area of soil improvement that is not represented in this session is improvement for environmental reasons. Environmental cleanups are now introducing an entirely new set of improvement methods, such as in situ vitrification, solidification or fixation, bioremediation, soil vapor extraction, pump and treat, and surfactant flushing. As discussed by Mitchell and Court (1992), "... techniques of soil stabilization and ground modification often used for solving traditional geotechnical problems are being adapted and utilized in new ways ....", referring to containment of wastes and the cleanup of hazardous waste sites. Future sessions of this case histories conference will likely have numerous topics in this area, and perhaps even sessions devoted to soil improvement for environmental purposes.

With these introductory comments in mind, this General Report for Session VII is presented in the following four sections. First, a summary of each paper categorized as being in Session VII is given. This summary is followed by a discussion of soil improvement validation techniques. The next section gives a summary of research needs in the general area of soil improvement. The final section of this General Report presents some concluding remarks regarding soil improvement.

[1] Indicates number(s) of papers from each country

REVIEW OF PAPERS

For the purpose of this General Report, the 30 papers have been divided into five main categories. These include:

- Grouting and other means of chemical stabilization
- Stone columns, sand columns, and vibroflotation
- Preloads, sand drains, and wicks
- Dynamic compaction
- Other methods

These categories of ground improvement are used so that the reader of this General Report will be able to quickly identify papers that are within an area of general interest. It should be noted that several papers cover procedures from more than one category. In this case, the paper is presented in the category that the authors seem to emphasize. For each case, particular note is made of procedures used to confirm or test the improvement method. These verification procedures range from post-improvement soil testing to construction and monitoring of test embankments. In some papers, monitoring of the constructed project is also reported.

Grouting and Chemical Stabilization

Six papers involve some type of grouting or other method of chemical stabilization. These include Papers 7.01, 7.09, 7.10, 7.11, 7.17, and 7.39. General contents of these papers are summarized below.

- *Paper 7.01 by Weaver, Kolbe, and Klein* describes grouting of unconsolidated landslide debris at a powerhouse facility in northern California. The primary purpose of the grout is to protect the landslide debris from scour and piping during high streamflows. A variety of grouting procedures were used to improve the site, including permeation grouting, displacement grouting, compaction grouting, and controlled hydrofracture. Over 150 borings were drilled, and 14,000 cubic feet of grout were placed. The success of the grouting program was verified by inclined borings and borehole water-pressure tests. Water takes were typically less than 3 to 4 gallons per minute after improvement.

- *Paper 7.09 by Kokkambaeng* discusses the restoration of a roadway embankment in Thailand. A 165-foot-long section of the embankment had failed during rapid construction. To improve the ground, a wet jet grouting method was used. This procedure involved a low-cement slurry (3 percent) to create columns that are approximately 4 feet apart and 20 feet deep. CPTs conducted before and after the improvement show nearly a 100 percent increase in strength between the columns. The embankment has performed adequately since improvement.

- *Paper 7.10 by Johnson and Pengelly* summarizes results of field stabilization treatment of two test pads near San Antonio, Texas. The program was conducted to evaluate methods for reducing the swell characteristics of clay. The tests involved injecting a proprietary potassium-based chemical grout and a lime slurry at 2- to 3-foot spacing in the two test pads. Posttreatment laboratory tests were conducted to evaluate the reduction in swell potential. Results show that both procedures reduced swell potential, with the potassium-based grout being more successful.

- ***Paper 7.11 by Wang, Qiu, Shi, and Liu*** discusses use of an alkali slurry to improve loess deposits at two sites in China. At one site approximately 140 boreholes were filled with hot (90°C) alkali liquid; at the other site four holes were filled with hot alkali. The purpose of the alkali treatment was to reduce compressibility and eliminate the collapse potential. After a 1-month curing period, loess samples were obtained at each site and tested in the laboratory. Changes in soil properties are presented for each site. Structures at both sites have performed adequately since ground improvement.

- ***Paper 7.17 by Chang, Basnett, and Carter*** summarizes procedures used to stabilize solution chimneys in karst terrain in Florida. Stabilization was carried out before constructing a sanitary landfill. Site investigations were conducted before ground improvement using SPT, CPT, and Ground Penetrating Radar (GPR) methods. Once the locations of potential voids were identified with the GPR and confirmed with the CPT, compaction grouting was used to improve the soil. CPT methods were used following grouting to confirm ground improvement. A geotextile was also placed at the site to reinforce small holes that may have been missed by the exploration methods. After completion of soil preparation, the landfill disposal area was flooded for over a week; no subsidence was observed.

- ***Paper 7.36 by Wu, Chen, and Feng*** presents results of a program in China where deep-soil mixing was used to stabilize the foundation of a 200-foot-diameter, 65-foot-high floating roof oil storage tank. Soil at the tank site consists of soft clay and silt to depths of 50 feet. Approximately 3,250 columns were placed to depths of approximately 50 feet on a 3.5-foot grid. Four load tests were conducted on the columns to determine allowable bearing capacity and settlement. Crosshole and SPT tests were conducted in the field to determine dynamic properties; resonant column and simple shear test were conducted in the laboratory. The laboratory tests included tests on soil-cement mixtures. Spectral-analysis-of-surface-wave (SASW) methods were used to determine the increase in shear wave velocity as a result of ground improvement. The shear wave velocity of the composite foundation was nearly 1,000 feet per second (fps) compared to the original ground velocity of 460 to 700 fps.

- ***Paper 7.39 by Colleselli and Varagnolo*** discusses procedures used to improve the foundation for a nearly 500-foot-tall telecommunications tower in Italy. The foundation is located on alluvial gravel and sand; differential and total settlement had to be controlled. Crosshole and SPT methods were used to characterized site conditions. Jet grouting methods were used to improve the soil. This involved installing 450 columns on a 3- to 8-foot grid to a depth of 85 feet. A plate-load test was conducted on one of the columns to determine deformation characteristics. Good comparisons are reported between results of finite element estimates and actual settlement measurements during construction.

Stone Columns, Sand Piles, and Vibroflotation

Nine papers deal with soil improvement using stone columns, sand piles, vibroflotation, or similar processes. These papers include numbers 7.04, 7.07, 7.18, 7.22, 7.23, 7.37, 7.40, 7.41, and 7.42. The general contents of these papers are summarized below.

- ***Paper 7.04 by Sreekantiah*** describes the use of vibroflotation at a fertilizer and chemical plant in India. The site consists of sand and clay to depths greater than 60 feet. An area of approximately 20 feet by 80 feet was improved on a 6- to 7-foot grid to a depth of approximately 25 feet. Vibroflotation was selected rather than driven piles because of potential damage to nearby buildings during pile driving. Bored sand compaction piles had been unsuccessfully attempted at the site. SPTs and CPTs were conducted before and after ground improvement. Plate-load tests (6-foot-diameter) were also conducted on the stabilized ground. Settlements were monitored during plant construction and found to be within tolerable limits.

- ***Paper 7.07 by Wang, Zheng, and Cui*** presents a summary of the use of stone columns at a site in China before construction of a large floating roof oil storage tank. The tank is approximately 200 feet in diameter and 60 feet tall. Soil at the site comprises a fill, "sandy loam," and siltstone. Over 1,600 stone columns were installed on approximately a 3- to 4-foot grid to an average depth of 16 feet. Dynamic penetration tests were conducted through the center of 85 of the columns to evaluate the quality of construction. Results of the penetration tests were correlated to results of plate-load tests (3.5- by 3.5-foot plate) to identify columns that would not meet a deformation criterion. The plate-load tests were conducted on the columns and between the columns. An area of the site not meeting the required settlement criterion was improved by excavating the upper 10 feet of soil and replacing this volume with a stone "mattress." Settlement of the tank has been monitored over the last year and has been acceptable.

- ***Paper 7.18 by Blanchard and Clements*** describes the use of stone columns to improve the liquefaction resistance of stratified silty soil at an elementary school site in California. SPTs and CPTs were conducted to evaluate site conditions. The upper 20 feet of soil were found to be liquefiable at an acceleration of 0.65g, which would occur during a maximum credible earthquake. Approximately 850 stone columns were installed in a triangular pattern on a 9-foot grid. SPTs and CPTs were conducted between columns after ground improvement. A stone columns test section was also constructed to evaluate improvement as a function of distance from the stone column. No improvement was recorded in the silty soil when spacing was reduced from 8 to 4.5 feet. Cyclic simple shear tests were also conducted to evaluate liquefaction resistance of the improved ground. The authors discuss the effects of redistribution of overburden stress through load transfer to the stone column and the reinforcing effects of the stone columns on soil rigidity.

- ***Paper 7.22 by Chen and Liu*** discusses the use of vibroflotation in China to increase the liquefaction resistance and bearing capacity of a very loose silty soil. A variety of procedures were used at the site to evaluate soil conditions before and after improvement, including SPTs, plate-load tests, in situ density tests, and pressure cell tests. The size of the plate-load tests varied from 2.5 to almost 6 feet in diameter. Results of the testing indicate that little improvement occurred at the site where the clay content exceeded 15 percent. Procedures for modifying bearing capacity and liquefaction strength of the soil to account for the vibroflotation columns are given. Within 6 months of constructing buildings at the site, a magnitude 7 earthquake occurred. No liquefaction or other earthquake-related damage was observed.

- ***Paper 7.23 by Wakame and Majima*** reports on the use of low-strength piles to improve ground at a housing development in the suburbs of Tokyo. The low-strength piles were constructed from granulated slag and 10 to 20 percent cement. Auger methods were used to install the piles. These piles have a permeability on the order of 1.5 to

2×10^{-3} centimeters per second, and consequently provide drainage as well as strength. The unconfined compressive strength of the pile material ranges from 1 to 10 tons per square foot, depending on cement ratio, relative density of the slag, and time of curing. Methods for designing the slag piles are summarized by the authors. Results of a vertical load test conducted on one of the slag piles are also presented.

- ***Paper 7.37 by Sarma, Somayazulu, and Sastri*** summarizes use of granular trenches and stone columns to improve ground beneath three bus stations in India. The granular trenches, described as a plane-strain version of the stone column, were used to support strip footings. The trench geometry was approximately 4 to 6 feet in width and nearly 15 feet deep. Stone columns were also placed at one of the sites at 3-foot spacing. Results of plate-load tests are given for the sites. Each program led to successful ground improvement.

- ***Paper 7.40 by Blanco, Villegas, and Sgambatti*** evaluates the use of compaction columns in a sand-clay profile in the Lake Maracaibo area of Venezuela. The primary design issue considered by the authors is the seismic stability of dikes. Compaction columns were installed at spacings of 7 to 15 feet to a depth of approximately 50 feet. Column installation involved vibro replacement and "casing-ramming" techniques. Methods of column construction, as well as spacing and pore pressure buildup, were studied. Soil characteristics were investigated before and after improvement using SPT, CPT, VST, and laboratory methods. Field instrumentation at the test sites included piezometers and inclinometers. More improvement was reported from the casing-ramming method.

- ***Paper 7.41 by Han and Ye*** presents a ground improvement case history for a 100-foot-diameter, floating roof oil tank near Shanghai, China. Prior to improvement, the site did not meet bearing capacity and liquefaction criteria. Stone columns were constructed at 5-foot spacing to depths of 25 to 35 feet. Soil conditions were evaluated using plate-load tests, CPTs, and SPTs. Settlement was also monitored at the center and edge of the foundation during filling of the tank. Pore pressure parameters were determined from the results of piezometer measurements taken during tank filling. Procedures for making these determinations are presented.

- ***Paper 7.42 by Verma*** describes ground improvement at two hydropower plant structures in India. At one site, replacement of unsuitable ground was used; at the other, granular piles spaced at 3 feet to depths of nearly 35 feet were used. Over 1,200 granular piles (1.5-foot-diameter) were installed **MANUALLY** by using augers, as suitable mechanical/hydraulic rigs were not available. SPTs were conducted to evaluate site conditions; plate-load tests were conducted to evaluate construction of the piles.

Preloading, Sand Drains, and Wick Drains

The next category comprises eight papers within the area of preloading, sand drains, and wick drains. The paper numbers for this category are 7.06, 7.12, 7.13, 7.14, 7.15, 7.16, 7.19, and 7.35. Contents of these papers are summarized below.

- ***Paper 7.06 by Shin, Kim, Shin, and Dass*** describes the use of sand drains and preloading for land reclamation at a steel mill in Korea. Drains were located at a 6- to 8-foot spacing and were installed to depths of 80 feet. The diameters of the sand drains were approximately 1.6 feet. Soil at the site is a soft clay. Preloading heights ranged from 3 to 40 feet. Settlement plates and piezometers were used to monitor soil behavior under the preload. The authors present comparisons between predicted and observed settlement. Methods used for stability control against base failure are also described. SPTs were conducted before, during, and after preload removal to show strength increases. Comments on construction quality assurance are also given.

- ***Paper 7.12 by Zhu, Pan, and Xie*** presents a summary of procedures used to improve soft ground using wicks and a preload at the Ningbo Airport in China. A test embankment with approximate dimensions of 250 feet by 350 feet was constructed. Soil behavior under the preload was monitored for 14 months using settlement plates, deep settlement gauges, and piezometers. Swell of the soil when the preload was removed was also monitored. The effects of hydraulic resistance and smear on wick design are discussed. The authors recommend that new equipment be developed to reduce smear. The new Ningbo International Airport began operations in 1990 and has not encountered settlement problems to date.

- ***Paper 7.13 by Ali and Huat*** evaluates the effectiveness of vertical drains at sites in Malaysia. Embankments were constructed to heights of 10 to 20 feet. Some areas beneath the embankments had wicks, others did not. Soil behavior was monitored with settlement plates, settlement gauges, inclinometers, and piezometers. The test program included different wick types, sand columns, and vacuum preload with wicks. Comparisons are given between VST strengths measured before and after preloading. Results show that some wicks are much more successful than others with respect to dissipating excess pore pressures. Differences in the results, including the effects of lateral pressure and consolidation settlement on drain performance, are discussed.

- ***Paper 7.14 by Yu*** describes methods for preloading organic soil and sand in southern Florida. The project site was reclaimed from a large mangrove swamp. CPTs, borings, tests pits, and laboratory tests were used to characterize soil conditions. Two test embankments were also constructed, each with a plan area of 100 feet by 120 feet and with heights of 10 feet and 15 feet. Results of the embankment tests were used to design rolling preloads for the site. Coefficients of secondary compression in the organic soil were evaluated for different preconsolidation ratios. The preload was also applied to a loose sand to remove nearly a foot of compression before construction. Good performance has occurred at the site since ground improvement.

- ***Paper 7.15 by Cloonan*** reports on the use of wicks and preloads at a site in the Port of Wilmington, Delaware. Soil conditions at the site consist of 10 to 15 feet of fill over 100 feet of soft soil. SPTs were used to characterize soil conditions at the site. Wick drains were installed to 50 feet at a 5-foot spacing. A 12-foot preload was used. Soil response to the preload was monitored using settlement plates, Borros settlement points, and piezometers. The height of preload was increased in areas where wicks could not be installed to the design depths. Borings were drilled through the preload to evaluate changes in strength and consolidation properties of the soil. A discussion of post-construction settlements is also given.

- ***Paper 7.16 by Bedenis*** presents another case history of the use of wicks and preload before construction of a large-diameter sewer line in Michigan. Soil conditions at the site consist of over 30 feet of compressible organic silt. A 12-foot fill was to be constructed over the sewer line. In view of the estimated settlement, wicks were installed at a 4-foot spacing in a triangular pattern; a 12-foot preload was then constructed before installing the sewer line. Soil behavior was monitored using vibrating wire piezometers and settlement gauges. The embankment was to be left in place long enough for settlement to equal the computed sum of primary consolidation and one logarithmic cycle of secondary compression. Results indicate that settlement occurred much more quickly than had been predicted.

- ***Paper 7.19 by Abedi, Risitano, Yamane, and Chin*** describes the use of wicks and preloads in the Boston area. Wicks were installed to depths of 70 feet in Boston Blue Clay. Wick spacing varied from 5 to 9 feet; a triangular pattern was used.

Fills up to 75 feet were used to load the site. Soil response was monitored with piezometers, settlement plates, Borros anchors, and spiral foot anchors. Extensometers and inclinometers were used to monitor rebound and lateral movement. SPTs were conducted following the preconsolidation program. Changes in the unconfined strength and the preconsolidation pressure for the improved soil are also shown.

- *Paper 7.35 by Yasuda, Suzuki, Takemoto, Hayashi, Saito, and Ine* describes improvement to a coal storage yard constructed on reclaimed land in northern Japan. SPT and CPT methods were used to characterize soil conditions. Cyclic triaxial and cyclic torsion tests were also conducted. Soil at the site was found to consist of sand, silt, and clay in a soft or loose consistency. Ground improvement was carried out to improve settlement and liquefaction performance. Methods of ground improvement included deep-well pumping and preloading with vertical drains for clayey soil, dynamic compaction to improve the sandy soil, and a sand compaction pile for intermediate soil. Test embankments were constructed to optimize the improvement method for the clayey soil. For these embankments, the effects of improvement on compressibility and strength were determined. A test section was also constructed to evaluate the dynamic compaction method. The coal facility has operated since 1985 with measured settlements being about half the prediction. The site has also undergone several earthquakes with accelerations up to nearly 0.1g without liquefaction.

Dynamic Compaction

Three authors described the use of dynamic compaction methods to improve ground. These case histories are described in Papers 7.02, 7.31, and 7.35. The last paper is summarized in the category involving **Preloading, Sand Drains, and Wick Drains** and will not be repeated here. However, readers who are specifically interested in dynamic compaction should not overlook this case history as it included a test section to evaluate this ground improvement method.

- *Paper 7.02 by Whetten* summarizes the use of dynamic compaction at a supermarket site in Troy, New York. The site is next to steep slopes by the Hudson River. Soil consists of miscellaneous fills from 1 to 27 feet in thickness. Site conditions were evaluated using SPTs. A 10-ton weight was dropped from a height of 25 to 80 feet. Four to six impacts were applied at a spacing of 6 feet. Verification SPTs were conducted after ground improvement. Vibrations during dynamic compaction were monitored and reported in the paper. A test program was conducted to verify that levels of vibration would not exceed levels that might result in damage to nearby structures. Pre- and post-damage surveys were also conducted. Results of the vibration monitoring indicate that predominant frequencies of vibration range from 10 to 25 Hz and that amplitudes of vibration decrease from the first to the second pass.

- *Paper 7.31 by Dumas, Beaton, and Morel* describes three case histories in Canada where dynamic compaction is used to create large-diameter, granular columns in the ground. The improvement method is referred to as hyper-compaction. It involves dropping the tamper to create a crater, filling the crater with granular soil, and then rehitting the soil. As many as 60 to 100 drops are eventually used. The granular columns are "driven" to depths of 20 feet or more at spacings somewhat larger than would be used for stone column design. Use of this method is reported at three sites in Canada. Pre- and post-ground improvement evaluations were conducted at the sites using combinations of SPT, CPT, BHT, DMT, and PMT methods. Soil at the sites ranged from sand to clay. Pore pressures were monitored during construction of the granular columns. Results demonstrate the success of this improvement method.

Other Topics

The final four papers involve a variety of topics, none of which is discussed by other authors within the session. These topics include ground improvement by the use of geotextiles (Paper 7.03), by blasting (Paper 7.24), by the use of grouted mattresses (Paper 7.38), and by use of electro-osmosis (Paper 7.44). Brief summaries of these papers are presented below.

- *Paper 7.03 by Murty, Mathur, Soni, and Rao* summarizes results of a study where the benefits of using geotextiles as part of roadway subgrades were determined. The purpose of the geotextile was to prevent pumping of fine soil into the subgrade. A field test was conducted at a site in India where the soil had a low bearing capacity and the water table was high. Combinations of geotextiles, sand bases, and reduced pavement sections were placed along a mile of roadway. Performance was recorded at 11 test sections. Test pits were later dug to examine the geotextile. Sections of the roadway with the geotextile showed better performance due to the ability of the geotextile to confine and restrain movement of the granular layers.

- *Paper 7.24 by Krjcer, Muhovec, and Pranjic* describes the use of blasting to improve ground as part of the construction of ground anchors. Anchor tests were conducted at two test sites in Croatia. Comparisons were made between pullout capacities of cylindrical anchors and anchors constructed by filling a small hole (created by an explosion) with concrete. The higher bearing capacity for the spherical anchor was attributed to densification or compaction of the soil from the explosion. The explosive method seemed to work better in clay soil than sand. Methods of analysis for the spherical anchor are given. Close comparisons were obtained between measured and predicted capacity for the spherical anchors.

- *Paper 7.38 by Shah, Shroff, and Parikh* describes the use of a grouted mattress to reduce water seepage in canals in India. The canals were already constructed and in operation. Ground improvement had to be accomplished without interrupting water flow. The mattress is about 4 inches thick and is grouted in place with a combination of portland cement and sand. Set time requires several hours. The authors present valuable information about optimizing the grout mixture for these mattresses.

- *Paper 7.44 by Lefebvre and Pavate* examines the effects of electro-osmosis on soft sensitive clay from eastern Canada. The program, which involves a series of laboratory tests, evaluates the strength, effective stress, and water content relationships after electro-osmosis at different voltages. Results are strongly affected by the location of the anode and cathode, with the strength increasing on the anode side and decreasing on the cathode side. Reversing the polarity throughout the test resulted in reductions of water content near the anode and cathode, but strength increase only occurred at the end last serving as the anode. Results are attributed to the physical-chemical response of the soil to the impressed voltage.

VERIFICATION OF SOIL IMPROVEMENT

One of the key elements of most of the soil improvement projects described in the preceding section was the need to verify that the improvement method was successful. Most of the authors resorted to some type of in situ testing method to evaluate the degree of improvement before construction of the final project was initiated. For special projects test embankments or test pads were constructed to confirm the degree of improvement before construction. Laboratory data were typically used to augment in situ information about ground improvement. The ultimate method of verification involved monitoring the performance of structures during and after construction. The following comments are offered on these methods of verification.

In Situ Testing Methods

Various in situ testing methods were used by the authors in this session to evaluate the degree of improvement. These included the SPT, CPT, BHT, VST, PMT, and DMT. Plate-load tests were also commonly used to evaluate the deformation characteristics of stone columns and similar improvement methods.

Two in situ testing methods, SPT and CPT, are routinely used throughout the world to evaluate the degree of ground improvement. These methods are generally preferred as they avoid the uncertainties associated with sampling and laboratory testing, and they are more widely available and understood than, say, the PMT and DMT methods. The CPT is particularly attractive because of the ability to rapidly obtain a continuous record with depth. As long as the SPT and CPT are performed in the same manner with the same equipment, they are assumed to provide a direct indication of changes in ground conditions. However, as suggested in Paper 7.18 and as discussed in a 1991 National Science Foundation (NSF) Workshop on **Soil Improvement and Foundation Remediation** (NSF, 1991), some care must used in making these interpretations. Time-dependent increases in stiffness, strength, and penetration resistance have been observed after densification. The report from the NSF workshop also notes that lateral stress conditions change during other types of ground improvement, such as grouting, and these changes also must be considered when comparing pre- and post-improvement soil conditions.

While the PMT and DMT are not used as frequently for post-improvement evaluations, at least one of the papers referred to these methods (Paper 7.31). Recent work by Hughes (1992) has suggested that important stress-strain information can be derived from the PMT even when borehole disturbance occurs. This suggests that, with proper interpretation, the PMT could be a valuable tool for obtaining changes in stress-strain characteristics of the soil following soil improvement.

Use of plate-load tests to evaluate the stiffness characteristics of stone columns was described in several papers. These tests are typically performed before and then after improvement. For the post-improvement case, tests were conducted either directly on top of the stone column or in between the columns. The sizes of the test plates ranged from the size of the stone column to 6 feet in diameter. Typically a settlement limit is set for an imposed load when developing an acceptance criteria. While these results appear to be easy to understand and interpret, care must be used in extrapolating the load-settlement data to the final design condition. Depending on the size and stiffness of the foundation system, deformations may or may not be representative of full-scale response.

One method of in situ testing received very little use as a verification tool-geophysical testing. Geophysical methods include seismic techniques, ground penetrating radar (GPR), and resistivity/conductivity methods (NSF, 1991). Of these methods, the seismic technique appears to have significant promise for evaluating ground improvement. The SASW method is particularly attractive as it can be used to obtain accurate shear wave velocity (or shear modulus) profiles without drilling boreholes. Wu and his colleagues used this method in China (Paper 7.36). Stokoe (1993) reports that he has used the SASW to identify voids behind tunnel linings, soft zones in pavement subgrades, the depth of ground improvement for dynamic compaction, and zones of lime stabilization in swelling clays.

Test Embankments and Test Pads

Test embankments and test pads are used in important programs to confirm methods of analysis. These methods of field verification involve testing small areas of the site to be improved using a prototype of the planned improvement method. It often represents the most reliable method for evaluating the benefits of ground improvement, although this method of verification is time consuming and expensive. Careful consideration must be given to the planning of any test embankment, particularly in developing instrumentation programs that provide meaningful data. Several of the papers in Session VII used this method of verification.

The most common example of this method of verification is the use of a test embankment with and without wicks to confirm the amounts and rates of settlement under different loading and drainage conditions. Alternatives such as using a vacuum, rather than earth, for the preload have also been applied (Paper 7.13). A large ground improvement project at the Port of Los Angeles has also recently tested the vacuum technique. The primary benefit of the vacuum method has been reduction in construction efforts associated with hauling the preload material onsite, and at the end of the project hauling it back offsite.

Various types of instrumentation were used by the authors to monitor soil response for the test embankments, including settlement plates, downhole settlement systems, piezometers. and inclinometers. While the selection and installation of instrumentation apparently was a simple task for most of the case histories in Session VII, as no authors reported difficulties with their instrumentation, many test embankments with poorly conceived instrumentation monitoring programs have resulted in little more than confusion about likely site performance. Dunnicliff (1988) provides an excellent basis for selecting suitable types of instrumentation and installation methods.

Test pad sections have become almost common place for methods that involve stone columns, vibroflotation, and compaction grouting. In these applications, the owner often uses a "performance specification" that identifies the minimum level of ground improvement, but does not necessarily specify the spacing or construction procedure. This offers the ground improvement contractor the opportunity to use experience gained on past projects to optimize the type and spacing of the improvement. Contract documents require that the improvement method be validated by meeting some minimum SPT or CPT value. Ideally, the importance of installation changes, such as spacing, is evaluated with the test pad program. Paper 7.18 presented an excellent example of this approach. Baez and Martin (1992) summarize a similar type of study.

Test pad sections can also be used to evaluate environmental impacts associated with construction. A good example of this consideration is the vibration associated with dynamic compaction. Although methods exist for predicting vibration levels for a given impact energy, these predictions depend strongly on site-specific conditions, such as the stiffness and damping characteristics of the soil and the type of structure that could be affected by the vibration. A test program where weights are dropped at progressively greater heights and at progressively closer distances to a structure of interest allows the vibration issue to be quantified before damage occurs. Contractors involved in dynamic compaction are generally accustomed to making such measurements or working with geotechnical consultants who are able to make the measurements. Paper 7.02 describes such a study. This paper also notes that pre- and post-improvement damage surveys were conducted for nearby structures. Such studies are essential for important structures.

Laboratory Testing

Clearly some types of laboratory tests must be conducted with a ground improvement program. These might include grain-size analyses, slump tests, and compaction tests. The decision to use laboratory tests to verify a strength increase or compressibility change requires more consideration.

Laboratory testing can be used to verify some types of ground improvement method, although it does not appear to be the preferred method. The primary disadvantage of the laboratory test is the disturbance that occurs during sampling, transport, and setup of the sample. However, some improvement methods, such as electro-osmosis and grouting, can be associated with changes in physical-chemical properties that are less effected by disturbance. Consequently, laboratory methods should not be ruled out of verification studies. Examples of laboratory testing to evaluate strength and compressibility changes after soil improvement are given in Papers 7.06, 7.10, 7.15, and 7.19.

Construction and Post-Construction Monitoring

The ultimate test of many of the ground improvement methods involves monitoring foundation response during and after construction. For most projects involving ground improvement, construction and post-construction monitoring is a routine occurrence. Typically, this monitoring includes settlement and pore pressure measurements. If measurements are within acceptable levels, monitoring is generally abandoned at the end of construction. This is often an unfortunate situation, as additional valuable information can be obtained about the long-term deformation characteristics if monitoring continues. However, the owner typically does not have the interest in paying for monitoring, and the engineer is not interested in doing the monitoring without reimbursement.

RESEARCH NEEDS

The following summary of research needs is based in a large part on the results of a National Science Foundation workshop held at the University of Washington in August of 1991 (NSF, 1991). The attendees at the workshop included 34 representatives from academia, government, and industry. The primary objective of the workshop was "*to provide a forum for the exchange of knowledge and experience among experts with a wide variety of viewpoints and perspectives on soil improvement and foundation remediation ....*" The specific goals included "*.... (1) to summarize the current state of knowledge concerning soil improvement ....., (2) to identify and evaluate current research needs and opportunities in these areas, and (3) to recommend future directions for research on soil and foundation remediation.*"

While many of the participants of this case histories conference may not be directly involved in research, it is thought that the research topics developed at the NSF workshop provide an indication of areas or topics of uncertainty when using ground improvement methods. The practicing engineer should, therefore, give careful consideration to some of the following issues as he or she plans or executes a ground improvement program. As ground improvement is carried out, some of the results of the ground improvement program may help answer these uncertainties. In these situations publication of the results in future sessions of this case history conference is strongly encouraged. For those specifically involved in research, but perhaps not aware of the 1991 NSF workshop report, the following overview will hopefully encourage the researcher to obtain the workshop report and subsequently pursue one or more of the areas requiring further research. The reader is referred to the NSF workshop report for additional details regarding discussions and conclusions from this excellent workshop.

Major Needs

Three major needs that are applicable across the spectrum of soil improvement and foundation remediation were identified. These include:

- The need for a well-documented database of quantitative information from case histories of both failures and successes
- The need for better methods of characterizing and describing the soil and foundation in situ
- The need for improved methods of verification of the effectiveness of the various soil improvement and foundation remediation techniques

These three needs still exist.

Densification Techniques

Some of the high-priority research needs in the area of densification include the following:

- Development of theoretical models for understanding the mechanics of densification
- Investigation of time-dependent strength gain in densified ground
- Development of nondestructive methods for verifying densification effectiveness
- Further development of testing to evaluate the liquefaction potential of coarse-grained soil
- Investigation of the role of vibrator frequency and amplitude in the densification process

Other areas warranting research consideration within the topic of densification include the following:

- Investigation of the role of residual lateral stress on the results of in situ tests
- Identification of soil types that can effectively be densified by explosives
- Development of improved verification by geophysical methods

Drainage Techniques

Recommendations were also developed for the general area of drainage. Some of the areas assigned high-priority research needs are summarized below:

- Improvement in the determination of soil properties required for drainage system design both before and after drain installation and before, during, and after a seismic event
- Investigation of the suitability of gravel drains and prefabricated geocomposite drains that are installed without vibration to mitigate liquefaction potential in vibration sensitive environments
- Investigation of properties and performance of drains after large seismic events
- Development of methods for quantification of drainage effectiveness of stone columns

Other drainage topics warranting research include the following:

- Rapid in situ determination of soil properties required for drain design
- Separation and quantification of the beneficial effects of densification and drainage with vibro-replacement and vibro-compaction techniques
- Investigation of long-term performance and durability of all types of drainage systems, including material durability and potential for physical, chemical, or biological clogging
- Development of means for simple verification of drainage system performance capability many years after installation
- Investigation of bent, crimped, and smeared wicks performance

Physical and Chemical Modification

Topics within this category include the following:

- Evaluation of the long-term durability of grouts and cementing materials
- Investigation of the effectiveness of cells or grids of improved soil
- Identification and characterization of layered or stratified soil and evaluation of their effects on groutability
- Procedures for verification of effectiveness of physical and chemical modification

Inclusions

The following topics were identified within this category:

- Investigation of reinforcing effectiveness of stone columns

- Investigation of mechanics of reinforcement pile-soil systems

- Evaluation of appropriate dynamic earth pressure coefficients for nailed and reinforced structures

CONCLUDING REMARKS

The area of soil or ground improvement currently provides one of the more interesting and challenging opportunities within the geotechnical profession. This is clearly demonstrated by many of the excellent case histories presented in Session VII. A review of these papers, as well as soil improvement papers in other conference proceedings and technical journals, will show that

- The area of soil improvement offers one of the few opportunities for the geotechnical consultant to be pro-active in the development of foundations systems for a site. By this it is meant that rather than designing a foundation for what is there, the geotechnical consultant can optimize not only the foundation but also the ground supporting the foundation.

- The area of soil improvement offers one of the few opportunities to be creative in selecting and designing a foundation system. New improvement techniques are constantly being suggested and tried. This has resulted in considerable economic benefit to the owner and, ultimately, to the public.

- The area of soil improvement offers, at least in the United States, one of the few opportunities for the geotechnical consultant to work cooperatively with a specialty construction contractor in meeting an owner's needs. Rather than working under normal designer - contractor (adversarial?) conditions, the skills of each profession are used to optimize the constructed project.

- The area of soil improvement offers growth potential, particularly now that environmental cleanups are finally going beyond the study phase. The geotechnical profession is particularly well-suited to lead this effort given its understanding of civil engineering and construction.

While the concepts for soil improvement may seem well-defined, there is still much to be learned in terms of methods of improvement verification, response of the improved soil under various types of loading, and long-term performance. Forums such as this conference are excellent mechanisms for conveying new information about soil improvement technologies to the profession, and therefore must be supported by practitioners and researcher alike.

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