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Deep Foundation Improvements: Design, Construction, and Testing

Melvin I. Esrig and Robert C. Bachus, editors

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Philadelphia, PA 19103
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Timothy D. Stark[1] and B. Michael Yacyshyn[2]

SPECIFICATIONS FOR CONSTRUCTING AND LOAD TESTING STONE COLUMNS IN CLAYS

REFERENCE: Stark, T. D. and Yacyshyn, B. M., "Specifications for Constructing and Load Testing Stone Columns in Clays," Deep Foundation Improvements: Design, Construction, and Testing, ASTM STP 1089, Melvin I. Esrig and Robert C. Bachus, Eds., American Society for Testing and Materials, Philadelphia, 1991.

ABSTRACT: The purpose of this paper is to provide guidelines for writing a performance specification for the construction and load testing of stone columns in cohesive soils. Specifications from five different sources, three specialty contractors and two agencies, were studied to develop the guidelines described herein. The two primary components of a performance specification are the performance criteria for the stone column foundation and the load testing procedures used to verify that the desired ground improvement has been achieved.

KEY WORDS: specifications, soil stabilization, vibro-replacement, cohesive soil, load tests

There are a number of construction techniques available to stabilize or improve soft clays. These methods include staged construction with and without prefabricated strip drains, geosynthetics, deep foundations, removal and replacement, and stone columns. Stone columns have been successfully used for a wide variety of projects and are becoming widely accepted as a stabilization technique for large area loads, such as embankments and fills. Stone columns may also be used to support spread footings. Stone columns are used to:

1.) reduce the total and differential settlement of the clay due to the applied load.

2.) reduce the time required for consolidation settlement to occur.

[1] Asst. Professor, Dept. of Civil Engineering, San Diego State University, San Diego, CA

[2] Senior Engineer, Kleinfelder, Inc., Irvine, CA

3.) increase the bearing capacity of the clay.

4.) increase the shear resistance of the clay which reduces the potential for slope instability.

The two major types of specifications used for the construction of stone columns are performance and procedural specifications. In a performance specification, the specialty contractor is required to improve the clay to: 1) provide a specified average bearing capacity, 2) limit the total and differential settlement to a specified value, or 3) provide a minimum factor of safety against slope instability. The specialty contractor then determines the most economical procedure to construct the stone columns, e.g. wet top-feed, dry top-feed or dry bottom-feed, that will provide the desired performance. The performance specification then specifies a load testing program to verify the ground improvement. If the testing program shows that the objectives have not been met, then it's the contractors responsibility to perform the additional work necessary to meet the specifications unless changed conditions were encountered.

A procedural specification provides the specialty contractor with a detailed description of the construction method, process, and the equipment that must be employed to complete the project. If the desired ground improvement is not achieved and the specialty contractor has followed the specifications, the owner/designer assumes the responsibility for this failure. Therefore, this type of specification requires that the designer possess an extensive knowledge of the nature and distribution of the cohesive soil that is to be improved, stone column construction techniques, and the anticipated performance of stone columns in the native soil. Developing this knowledge usually requires a test program where several stone columns are constructed using different vibrators, spacings, and construction techniques. The columns are then load tested to determine which equipment, procedures, and spacings will provide the desired ground improvement. Because this testing can be expensive, procedural specifications are usually only used on very large ground improvement projects where the cost of the initial load testing can be justified. However, procedural specifications may result in savings on stone column construction costs because the majority of the uncertainties associated with the construction are eliminated prior to contract bidding.

The authors feel that developing procedural specifications requires an intimate knowledge of stone column construction that most practicing geotechnical engineers do not possess. More importantly, procedural specifications often limit the specialty contractor's ability to use a new or unique construction method that may be capable of meeting the project goals at a reduced cost and/or time. Therefore, a performance specification is currently recommended and this paper provides the background required to develop a comprehensive set of performance specifications for stone column construction in cohesive soils. Procedural and performance specifications from five different sources, three specialty contractors and two agencies, references [1-5], were used to develop the "guide" performance specification described herein.

Specifications from successful and unsuccessful projects were reviewed during this study. Both the successful and unsuccessful specifications had formats similar the guide specification presented herein. However, the successful specifications contained more site specific information which facilitated the bidding and construction processes. Therefore, each section of the performance specification should contain as much site specific information as possible. In addition, any site specific laws or ordinances should be clearly identified.

Guide Performance Specification

The guide performance specification consists of the following eleven sections: 1.) soil improvement objectives, 2.) specialty contractor qualifications, 3.) scope of work, 4.) requirements of regulatory agencies, 5.) submittals, 6.) construction of stone columns, 7.) materials, 8.) obstructions, 9.) quality control and assurance, 10.) payment, and 11.) load tests and insitu testing. The following paragraphs describe the information that should be included in each section.

Soil Improvement Objectives

This section should clearly describe the proposed project, the area covered by the project, and the known subsurface conditions. The subsurface information should include representative cross-sections, soil properties, and boring logs or insitu test results. Any laboratory test results, e.g. undrained shear strength, preconsolidation pressure, water content, etc., should be clearly presented on the cross-sections. This section should also clearly describe the expected performance of the stone column foundation and the major responsibilities of the contractor. The performance criteria could require the stone columns to provide any combination of the following: 1.) an average allowable axial capacity, typically 20 to 30 tonnes per column in soft to medium stiff clays, 2.) an average bearing pressure, typically 150 to 200 kN/m^2, 3.) a total settlement that is less than a specified value, typically 25 to 100 mm, 4.) a limiting differential settlement, a typical angular distortion for soft clays is 1/300 to 1/500, and/or 5.) a minimum factor of safety, usually 1.5, against slope instability. Discussion of these typical values is provided by Barksdale and Bachus [6] and Mitchell [7]. The stone column spacing and layout required to achieve the specified performance is determined by the specialty contractor. However, if there are structural concerns that override the geotechnical concerns, limiting column spacing and diameter can be specified by the geotechnical engineer.

Specialty Contractor Qualifications

This section should specify that the stone column construction must be performed by a contractor that has a history of specializing in this type of construction. The "specialty contractor" should be required to submit proof of three or more projects of a similar nature on which they have successfully installed stone columns within the last two to three years. With the proof, the specialty contractor should submit the names, addresses and telephone numbers of previous clients who can be contacted, and are familiar with the project and the contractor's performance. A list of specialty contractors who meet the aforementioned qualifications can also be included in this section. This pre-qualification clause may limit the number of respondents to the project, but the complexity and desired quality of the work should justify this. It should be noted that this type of prequalification may not be permitted on federal projects.

Scope of Work

This section should outline the entire scope of work that will be performed by the specialty contractor. The principal items of work may include some or all of the following:

1.) Preparation of construction drawings showing specific stone column locations, identification numbers and approximate depths.

2.) A detailed description of the equipment and procedures to be used to achieve the desired construction performance criteria.

3.) Furnishing crushed stone (or gravel) as required for the stone columns and, if necessary, the working pad.

4.) Control and disposal of surface water resulting from stone column construction operations.

5.) Site access and construction of gravel working platform, if necessary.

6.) Control and disposal of surface water resulting from stone column construction operations.

7.) Construction and removal of silt settling ponds or similar facilities as required, and site restoration.

8.) Load testing of stone columns prior to and during production as specified.

On most projects, the installation of all stone columns should be the responsibility of one specialty contractor and no part of the contract should be sublet without prior approval. Multiple specialty contractors may be necessary on very large projects to achieve the desired schedule. The specialty contractor should also furnish a qualified supervisor, who is on the job-site at all times during construction, all labor, equipment, materials, and related engineering services necessary to perform all ground improvement work.

Requirements of Regulatory Agencies

This section should describe any laws, ordinances, or any other regulatory requirements that the specialty contractor must comply with during the project. For example, the specialty contractor could be required to comply with all requirements pertaining to the prevention of nuisance to the public and adjacent property owners by noise, impact, vibration, dust, dirt, water, and other causes. Another example would be specifying that the specialty contractor must comply with all laws and regulations pertaining to surface runoff, siltation, pollution, and general disposal of the effluent from the construction of the stone columns and general site work.

Submittals

This section should describe all the submittals that the specialty contractor will be required to provide throughout the contract. The submittals that may be required include:

1.) proof of expertise in constructing stone columns.

2.) construction drawings showing stone column locations, approximate depths and identification numbers.

3.) a description of the equipment and construction procedures to be used.

4.) certification that the installation crew has had experience in performing the work specified.

5.) printed copies of manufacturers recommendations for installation or use of special equipment. For example, the installation procedure, specifications and/or a sample of the filter fabric which might be used in the working platform.

6.) the source and material properties of the backfill material.

7.) daily reports of the progress which include stone column locations, start and stop time, tip depth below grade, and stone quantity per location.

Construction of Stone Columns

A section describing the appropriate construction methods and techniques used for stone column construction should be provided. This is especially important if site constraints or project objectives preclude the use of one or more of the methods. The site constraints should be clearly stated in the section entitled Soil Improvement Objectives. It should be emphasized that a good performance specification will not unnecessarily limit the construction method and equipment that can be employed. The implications, if any, of selecting one method over the other on the performance of the finished product should be discussed in this section. However, the specialty contractor should ultimately decide on the method to employ. The minimum equipment necessary to construct the stone columns, and the column layout and minimum spacing can also be recommended in this section. There are currently three basic methods for constructing stone columns in cohesive soils:

1. Wet top-feed.
2. Dry top-feed.
3. Dry bottom-feed.

The wet top-feed method, also referred to as the vibro-replacement method, entails the use of water as a jetting fluid to aid probe penetration to the desired depth, maintain hole stability, and to facilitate gravel/stone distribution. After the hole is flushed out, stone is added in 0.3 - 1.0 meter increments and densified with a vibrator near the bottom of the probe. The wet top-feed method is usually used in very soft soils with a high ground water table where borehole stability is questionable. The wet, top-feed method is usually the fastest of the three methods, it typically results in the largest diameter stone columns (typically 0.7 to 1.1 meters in diameter), is capable of supporting the highest design load per column, and allows the use of the widest range of stone/gravel material gradations. However, this method requires a large quantity of water, 2000 to 4000 gallons per hour per probe, which may affect site trafficability and may require special handling to avoid polluting local watercourses.

The dry top-feed method, also referred to as the vibro-displacement method, is essentially the same as the wet top-feed method, except air is used as a jetting fluid. Thus, this method is much cleaner than the wet top-feed method and does not require disposal of the jetting fluid. However, this method can only be used where the borehole can stand open when the probe is extracted so the stone can be inserted into the hole. This usually requires cohesive soils with a minimum undrained shear strengths of approximately 50 - 60 kN/m^2, Barksdale and Bachus [6], and/or a fairly deep ground water table. The dry top-feed method is slower than the wet top-feed method and, if the probe must be kept in the ground to maintain hole stability, the maximum particle dimension of the stone/gravel material may be limited to 2.5 cm by the probe/hole clearance.

The dry bottom-feed method is similar to the dry top-feed method except the stone/gravel material is conveyed to the tip of the probe using an eccentric tube attached adjacent to the probe. Therefore, the vibrator prevents caving of the hole and as a result this method can be used in very soft soils with a high ground water table. Air is used to aid initial penetration of the probe and to facilitate movement of the stone/gravel through the tube to the probe tip. The air pressure should be limited to no more than 275 to 415 kN/m^2 to prevent fracturing of the clay mass during stone column construction (this limiting value tends to be site specific and should be evaluated on a case-by-case basis). Due to the absence of a jetting fluid, the resulting stone columns have diameters that are approximately 15 to 25 percent smaller than the wet top-feed columns. The dry bottom-feed method is slower and requires more equipment than the wet method. However, this method is much cleaner, does not require the disposal of a jetting fluid and results in stone columns with fairly consistent diameters. The dry method also does not introduce additional water into the soft cohesive soils.

Materials

i.) Stone/Gravel Requirements

The construction method usually influences the gradation of the stone/gravel. Stone having a maximum particle dimension of 5 to 10 cm can be used with the wet top-feed and the dry top-feed methods. The size of the tube that transports the stone to the probe tip will limit the maximum particle dimension to no larger than about 2.5 cm in the dry bottom-feed method. In all methods, the stone should be angular, hard, unweathered, and free from organic or other deleterious materials. The fines content for any of the construction methods typically ranges from 0 to 10 percent of the minus No. 4 fraction. Two gradations, adapted from Barksdale and Bachus [6], which would be acceptable for the wet and dry top-feed methods arepresented in Table 1.

A gradation for the dry bottom-feed method can be obtained by reducing the maximum size particle in the above gradations such that it corresponds to the diameter of the tube transporting the stone. The designer should verify that the specified material gradation is locally available.

TABLE 1 -- Acceptable Backfill Gradations for Wet and Dry Top-Feed Methods.

Sieve Size (cm)	Alternative 1 Percent Passing	Alternative 2 Percent Passing
8.9	100	---
7.6	90 - 100	100
5.0	40 - 90	90 - 100
2.5	---	50 - 90
1.9	0 - 10	35 - 70
1.3	0 - 5	---
0.95	---	0 - 10

The specialty contractor should furnish the geotechnical engineer with a gradation curve (ASTM D422), a specific gravity (ASTM C127), and the loose and compacted densities (ASTM C29) of the proposed backfill material. The percent weight loss of the stone should not be more than 12 percent when subjected to the sulfate soundness test (ASTM C88). When subjected to the Los Angeles Abrasion test (ASTM C131), the stone should have a maximum loss of 40 percent at 500 revolutions. The latest version of the specified standards should be used for these tests.

ii. Working Pad Material

When treating soft cohesive soils, a working pad may be required to:

1. provide adequate support for the construction equipment.

2. to better distribute the working loads from the structure or embankment to the stone columns.

3. serve as a drainage blanket during subsequent consolation of the cohesive soil.

The thickness and material gradation of the working pad is a function of its eventual use. Many designers have used geosynthetics and fabrics to provide tensile reinforcement and filtering as necessary. The gravel used for the working pad should be hard, unweathered, and free of organics or other deleterious material. The gradation of the working pad material may be similar to the material required for the stone columns. However, the working pad material should not be large enough to hinder probe penetration.

Obstructions

The vibratory probes can be misdirected or meet refusal during penetration on in-situ debris that has a maximum particle dimension of 15 to 20 cm. Pre-drilling is usually required through dense or hard soil zones to provide probe access to other layers requiring treatment. Pre-drilling can also be used successfully through debris-laden zones. The author's experience indicates that the increased rate of the stone column production typically compensates for the pre-drilling costs. When pre-drilling is not appropriate, and obstructions are encountered, the obstruction may be removed or the effected stone column may be relocated. If the obstruction is removed, the void should be backfilled with gravel.

Quality Control and Assurance

This section should detail the requirements of a quality control and assurance program. The program could consist of the following items.

i.) Construction Records:

Detailed records regarding the construction and load testing of each stone column should be required. This information typically includes:

- stone column identification number.
- date.
- elevation of top and bottom of each stone column.
- quantity of stone placed in each stone column.
- estimate of ground heave or subsidence.
- vibrator power consumption during penetration and compaction.
- time to penetrate and time to form each stone column.
- jetting pressure (air or water).
- details of obstructions, delays, and any unusual ground conditions.
- as-built drawings showing specific stone column locations, identification numbers, and estimated depths.
- load test results and calculations.

ii.) Workmanship:

The specialty contractors workmanship can be evaluated in a qualitative manner by full-time observation of the procedures, methods, equipment, and construction rates during stone column production. If an initial pre-production load test program was performed and accepted, then the specialty contractor must employ similar construction techniques for the production phase of the stone column construction.

iii.) Tolerances:

The authors feel that specifying allowable tolerances for horizontal control, verticality, average stone column diameter, and maintenance of previous subgrade elevations should be included in a performance specification. These factors may impact the ultimate performance of the stone columns, but are difficult to evaluate through load tests or insitu testing. The intent of the stone column construction plays a key role in selecting the appropriate tolerances. Some typical tolerances are listed below and are applicable to sites where there are not significant soil variations:

Horizontal Control:	1/3 to 1 diameter
Verticality:	1 to 5 percent deviation
*Stone Column Diameter:	-10 percent
Subgrade Elevation:	7.5 to 15 cm

*Note: Oversized stone column diameter is only a concern when there is a separate pay item.

Physical measurements in the field are required to maintain horizontal control and subgrade elevation. Verticality is usually judged by observing the tilt of the probe as it penetrates into the ground. If the tilt is excessive and may result in a stone column exceeding the specified vertical tolerance, an additional stone column may be required or the pattern locally altered to provide the proper support. The average stone column diameter may be estimated from the volume of the stone/gravel material delivered into a single stone column and the assumed relative density of the in-place material.

Payment

A lump sum basis of payment is typically used with a performance specification. The lump sum basis of payment allows the specialty contractor to select the most efficient method of stone column construction to satisfy the performance criteria. However, the area and depths of improvement and the performance criteria must be clearly defined if a lump sum price is used. The lump sum should provide full compensation for furnishing all labor (including a qualified supervisor), materials, tools, supplies, equipment, and incidentals necessary to design, install, and proof test the stone columns constructed during the production phase of the construction. The effluent handling and disposal, and the initial load testing can be covered in a lump sum price or as a separate pay item depending on the project.

Load Tests and Insitu Testing

One of the most important parts of a performance specification is the load test program that should be used to verify the performance of the stone column foundation. A combination of load tests on stone columns constructed before, during, and after production should be specified to verify the design assumptions and the performance specification. There are three major types of load tests: (1)

short-term tests which are used to evaluate the ultimate bearing capacity, (2) long-term tests which are used to measure the consolidation settlement characteristics, and (3) horizontal or composite shear tests which are used to evaluate the composite stone-soil shear strength for use in stability analyses. The most common of these tests is the short-term load test on a single column. The five specifications reviewed during this study all specified short-term load tests that were generally in good agreement with the ASTM Standard D1194-87, entitled "Bearing Capacity of Soil for Static Load and Spread Footing." Table 2 shows the variations observed in the short-term load test procedures reviewed.

The short-term load tests should be performed after all excess pore pressures induced during construction have been dissipated. The load increment should closely correspond to the actual loading. For example, if the actual foundation load will be applied very slowly a load increment of approximately 10% should be used. A rapid loading may result in immediate settlement as well as consolidation settlement. If the actual load will be applied rapidly, a load increment of 20 to 25% should be used. A final acceptance criteria of 2.5 cm of settlement at 150 to 200% of the allowable/design load appears to be a reasonable criterion.

The ultimate or long-term settlement of the stone column foundation is usually estimated from the results of short-term load tests on single stone columns. Mitchell [7] reported that the ultimate foundation settlement due to a uniform loading of a large area was 5 to 10 times greater than the settlement measured in a short-term load test on a single column. However, there is very little field data available to confirm this behavior. Therefore, it is recommended that long-term load tests on a group of columns be conducted in conjunction with short-term load tests to develop an estimate of the ultimate settlement of the stone column foundation. The long-term load tests should be conducted on a minimum of three to four stone columns located within a group of 9 to 12 columns having the proposed spacing and pattern. The load should be applied over the tributary area of the columns and left in place until the cohesive soil reaches a primary degree of consolidation of 90 to 95%. The applied load could consist of column backfill material, native material, and/or the dead weight from the short-term load tests. The results of these tests will provide valuable information for estimating the ultimate settlement of the stone column foundation.

During the production phase of construction, one short-term load test is usually performed for every 5 to 10% of the stone columns installed. These tests are referred to as proof tests and are used to verify quality control during production. The load applied in the proof test is usually only 100 to 125% of the allowable/design load.

Insitu testing to evaluate the affect of the stone column construction on the native cohesive soil can be also specified. However, the specified test method should be selected on the basis of its ability to measure changes in lateral pressure in cohesive soils. The electric cone penetrometer (CPT), the flat plate dilatometer (DMT), and the pressuremeter (PMT) appear to provide the best means for measuring the change, if any, in lateral stress due to stone column construction. Due to the limited amount of information that will be obtained from CPT, DMT or PMT testing after column construction, it is recommended that long-term load tests on groups of stone columns be conducted instead of insitu tests. However, extensive insitu testing should be conducted during the initial subsurface

investigation to reliably estimate the soil profile and the stone column design parameters.

TABLE 2 -- Variations Observed in Short-Term Load Test Procedures.

Parameter	Variation
Number of columns tested	3 - 5 (approximately one for each 100-150 columns)
Column configuration	single column to center column of a group of 9
Maximum load applied	100, 125, 150, and 200% of allowable/design load
Load increment	10 - 25% of allowable/design load
Load increment criterion	settlement less than 0.025-0.05 cm per hour
Final load increment criterion	0.013 - 0.025 cm per hour
Final acceptance criterion	total settlement less than 0.5 - 2.5 cm under 150 - 200% of the allowable/design load.

Summary

A procedural specification requires an intimate knowledge of stone column construction and performance that most practicing geotechnical engineers do not possess. In addition, a procedural specification may limit the contractor's ability to use a new or unique construction technique. As a result, a performance specification is currently recommended for the construction of stone columns in cohesive soils. The purpose of this paper is to provide guidelines for writing a performance specification. Specifications from five different sources, three specialty contractors and two agencies, were studied to develop the guidelines described herein. The performance specification consists of two main parts: 1.) The performance criteria for the stone column foundation, and 2.) the load testing program that should be used to verify that the ground improvement has been achieved.

The performance criteria clearly states the expected performance of the stone column foundation. This could require the stone columns to: 1.) provide a specified average axial capacity or bearing pressure, 2.) limit the total and differential settlement to a specified value, and/or 3.) provide a minimum factor of safety against slope instability.

The load test program should be specified such that the level of ground improvement can be evaluated. At present, it is very difficult to extrapolate the results of short-term load tests on single stone columns to the long-term behavior of the stone column foundation. As a result, a load test program involving long-term load tests on stone column groups is recommended to measure the ultimate settlement and capacity of the stone column foundation. The long-term tests could be conducted on three to four stone columns located within a group of 9 to 12 columns having the proposed spacing and pattern.

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Barry C. Slocombe, and Michael P. Moseley

THE TESTING AND INSTRUMENTATION OF STONE COLUMNS

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ABSTRACT: The vibro replacement technique for constructing stone columns was first used in Europe in the late 1950's and has been used extensively for ground improvement work in the United Kingdom for over twenty five years. Testing of ground improvement work is a vital ingredient of the construction process, and this paper sets out current British developments.

KEYWORDS: Vibro replacement, ground improvement, testing, instrumentation.

Compaction of clean sands using depth vibrators has been practised for over fifty years and commenced with the development of the key tool, the depth vibrator, by Johann Keller GmbH, Germany, in the 1930's. The concept of adding stone during compaction, first performed in the late 1950's, greatly extended the range of soils capable of being improved. This technique, commonly described as vibro replacement, is the predominant type of ground improvement used in the United Kingdom.

METHOD OF CONSTRUCTION

The depth vibrator, electrically or hydrostatically driven, and hung from a mobile crane, enters the ground under the combined effect of weight, vibration and air or water jetting. On reaching the design depth, a charge of imported stone is placed in the ground and the vibrator is used to compact the stone (and surrounding ground if

Barry Slocombe is Senior Geotechnical Engineer and Michael Moseley Business Development Director, Keller Group Limited, Oxford Road, Ryton-on-Dunsmore, Coventry CV8 3EG, England.