Summary of Transmission Line Structure Foundation Research

Prepared by
Cornell University
Ithaca, New York
Summary of Transmission Line Structure Foundation Research

EPRI's transmission line structure foundation research has led to major research advances, significant design/analysis improvements, and substantially new recommendations in areas ranging from analytical modeling to soil property evaluation and foundation load testing. This report presents the key points of 30 EPRI reports on soil and foundation behavior as well as a summary of the complete technology transfer to date.

BACKGROUND During the late 1980s, EPRI's transmission line foundation research project (RP1493) was initiated in response to industry requests for improved analysis and design capabilities in this area. Initially, the project addressed static axial loading in uplift and compression modes, with an emphasis on drilled shaft foundations. Subsequently, the project was expanded to encompass lateral, moment, torsional, and combined loading modes along with spread foundations in uplift mode and cyclic loading.

OBJECTIVES To present a brief overview of the objective, scope, and results of each task associated with the transmission line structure foundation research effort; to compile a comprehensive technology transfer list.

APPROACH The principal investigator reviewed reports, technical papers, and other technology transfer information pertaining to EPRI project RP1493-04. He then prepared a summary of the objectives, scope, and results of the various tasks associated with this project.

RESULTS This EPRI research, which extended from 1979 to 1995, has resolved many uncertainties in the industry's understanding of foundation engineering of transmission line structures. This report describes the breadth and depth of the research effort and summarizes project results and technology transfer to date. Key areas covered in the 30 EPRI reports published under this project include: analytical modeling; load testing; soil property evaluation and probabilistic modeling; reliability-based analysis/design; drilled shaft behavior under compressive loads; uplift, lateral, moment, and combined loading modes for both static and cyclic loading; and grillage foundation behavior in static uplift mode.

EPRI PERSPECTIVE Results of EPRI's transmission line foundation research will help designers select methods most appropriate to their specific geotechnical environments. In addition, the results will help designers evaluate existing foundations for upgrade studies. Basic EPRI research on drilled shaft foundations has been published in EPRI reports EL-2870, EL-3771, EL-5915, and EL-6800 among others.
PROJECT
RP1493-04
EPRI Project Manager: Anwar Hirany
Transmission Business Unit
Power Delivery Group
Contractor: Cornell University/Geotechnical Engineering Group

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Summary of Transmission Line Structure Foundation Research

TR-105206
Research Project 1493-04

Final Report, September 1995

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ABSTRACT

An overview is presented of the general accomplishments of EPRI Research Project RP1493-4. A brief summary also is included of accomplishments under RP1493-1,2,3. The breadth and depth of these research efforts are described, and the project output is summarized. Basically, this project has led to major research advances, significant analysis/design improvements, and substantially new recommendations in the following areas: analytical modeling, load testing, soil property evaluation and probabilistic modeling, reliability-based analysis/design, drilled shaft behavior under uplift, compression, lateral, moment, and combined loading modes for both static and cyclic loading, and grillage foundation behavior in static uplift loading. Key points on these topics are noted, and the complete technology transfer to date is summarized.
ACKNOWLEDGMENTS

The authors appreciate the assistance of numerous people during the course of this research project. Although specific task contributions have been noted in each of the preceding thirty technical reports, we want to note broad contributions to the overall success of this RP1493 effort. First and foremost has been the help and encouragement of our EPRI project managers [P.G. Landers (1979-83), V.J. Longo (1983-92), R.M. McCafferty (1992-93), and A. Hirany (1993-95)] and our ESEERCO project managers [K.C. Drzewiecki (1986-88) and B.R. Hart (1992-95)]. We very much appreciate their support of and commitment to our research and development efforts. We also appreciate the contributions of our many task force, industry, and consultant advisors over the years. Special thanks are due the following advisors for their outstanding assistance over extended periods of time: J.I. Adams, Consultant, formerly of Ontario Hydro; A.M. DiGioia, Jr., GAI Consultants; B.R. Hart and the late F.G. Picciano, New York State Electric & Gas; E.B. Lawless, III, Consultant, formerly of Potomac Electric Power Company; T.E. Rodgers, Jr., Consultant, formerly of Virginia Power; J.W. Rustvold, Bonneville Power Administration, and J.J. Wolf, Western Area Power Administration.

At Cornell University, we have benefited by having a succession of outstanding graduate students, visiting researchers, and faculty colleagues who have contributed enormously to this project. The students who earned degrees under this project are listed in the report appendix. Our geotechnical colleagues, T.D. O’Rourke and H.E. Stewart, have always contributed generously to all of our EPRI efforts. And our word processors (L. Crouse, L. McCall, and K.J. Stewart) and graphic artist (A. Avcisoy) have done outstanding jobs in preparing the various project reports.

Finally, K.J. Stewart prepared this report text, and A. Avcisoy assisted in report preparation. Several colleagues responded to a request for review and evaluation of the first draft of this report. These included: D.H. Beason, Alabama Power; A.M. DiGioia, Jr., GAI Consultants; B.R. Hart, New York State Electric & Gas; J.J. Wolf, Western Area Power Administration; and A. Hirany, EPRI Project Manager.
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APPENDIX A - TECHNOLOGY TRANSFER LISTING

A-1
Section 1

INTRODUCTION AND BACKGROUND

During the late 1970s, Research Project RP1493 was conceived within EPRI in response to industry requests for improved analysis and design capabilities for the foundations of electrical transmission line structures. The initial scope of this project was to focus on static axial (uplift/compression) loading, primarily addressing drilled shaft foundations. Subsequently, the project was expanded to encompass other loading modes (lateral, moment, torsional, combined) and cyclic loading. Spread foundations in uplift were to be included, if possible.

The first phase of this study was RP1493-1, which began in 1979. This initial phase was essentially a state-of-the-art assessment of foundation engineering for transmission line structures, with emphasis on uplift/compression loading. This assessment resulted in EPRI Report EL-2870 (A1)* and a major compilation of available load test data (A2). Subsequent studies under RP1493-2,3: (a) provided a critical evaluation of the uplift/compression design methods in EL-2870 using the accumulated database (A3), (b) developed techniques for evaluating load transfer in rock sockets and anchors (A4), (c) assessed procedures for predicting foundation uplift movements, again using the accumulated database (A5), and (d) provided a first look at drilled shafts in clay under static axial loading (A6).

Using primarily the initial state-of-the-art assessment from RP1493-1, supplemented by the RP1493-2,3 studies, a major research effort was outlined by EPRI to attempt to resolve, in comprehensive form, many of the uncertainties and large knowledge gaps in our understanding of foundation engineering for transmission line structures. This effort was delineated as RP1493-4 and was to be about a 7.5-year project, commencing at the beginning of 1983 and ending by mid-1990. The project initially had six tasks:

1 - Analytical Modeling
2 - Load Test Manual
3 - Soil Property Evaluation
4 - Foundation Load Testing
5 - Design Procedures
6 - Technology Transfer

The general scope of the overall final project is described in Figure 1-1. As can

*Refers to reference numbering in appended Technology Transfer list, beginning on page A-1.
TRANSMISSION LINE STRUCTURE FOUNDATIONS RESEARCH
AT CORNELL UNIVERSITY (EPRI RP-1493)

![Diagram showing research outline]

EXPERIMENTS  →  DESIGN METHODS  →  DESIGN AIDS

Figure 1-1. RP-1493 Research Outline

be seen, the research plan was to build on existing knowledge, conduct a wide range of experiments (analytical, laboratory, field, probabilistic), and develop improved design methods that could be implemented in user-friendly software. The software development was outside the scope of RP1493-4 and was done under RP1493-6.

Tasks 3 and 4 initially had significant field testing components, but these field efforts were deleted early in the study because of budgetary restrictions. Instead, Task 3 was re-directed to focus on soil property evaluation and probabilistic modeling, and Task 4 was re-directed to focus on large-scale model testing in large test chambers in the laboratory.
Several other significant changes occurred during the project as well. First, the starting date was delayed, and the actual start-up occurred on only a limited basis in Fall 1983. Second, budget cuts occurred in two successive years during the mid-1980s, causing the field testing deletions noted above and significantly delaying other task efforts and start-ups. Third, an opportunity presented itself in 1986 when the Empire State Electric Energy Research Corporation (ESERCO) agreed to co-fund an additional task on field testing of existing grillage foundations. Fourth, another budget cut occurred in 1991. Fortunately, ESERCO again stepped in and agreed to co-fund the continuation of certain sub-tasks within the project.

The final project tasks and sub-tasks and their status are given in Table 1-1. Tasks and sub-tasks that were added during the project are delineated by asterisks. The field testing in Tasks 3 and 4 that was eliminated early in the project is not shown in this table. Task 1e was eliminated in 1991, and Task 5 was re-defined at that time. Initially, Task 5 was to have concluded with an integration of all of the research results into an update of the EL-2870 report to provide a single, comprehensive, reference document that would represent the state-of-the-art of foundation engineering for transmission line structures at the conclusion of RP1493-4. This synthesis design manual (Task 5d) was terminated. In its place is this summary report (Task 5e), which provides a brief summary of all of the research efforts in RP1493-4 and directs the reader to the appropriate EPRI reference sources.

In the following sections of this report, a brief overview of each task effort is given, following the order shown in Table 1-1. Concluding comments end this report, to which is appended a comprehensive Technology Transfer List.
### Table 1-1

**PROJECT CHART FOR RP1493 AS OF MAY 1995**

#### A. PROJECT CHART FOR RP1493-1,2,3 (1979-83)

<table>
<thead>
<tr>
<th>TASK</th>
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<tbody>
<tr>
<td>Basic Design Practice Manual</td>
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<tr>
<td>Field Load Test Summary</td>
</tr>
<tr>
<td>Critical Evaluation of Design Methods</td>
</tr>
<tr>
<td>Load Transfer in Rock Sockets/Anchors</td>
</tr>
<tr>
<td>Uplift Movement Evaluation</td>
</tr>
<tr>
<td>Shafts in Clay, Static Axial</td>
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#### B. PROJECT CHART FOR RP1493-4,6 (1983-1995)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1ab - Axial, Lateral, Torsional Loading</td>
</tr>
<tr>
<td>1c* - Behavior of Shafts in Rock</td>
</tr>
<tr>
<td>1d* - Reassessment of Load Test Case Histories</td>
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<tr>
<td>1e* - Boundary Value Parametric Study</td>
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<table>
<thead>
<tr>
<th>TASK 2 - LOAD TEST MANUAL (FOR PROPER CONDUCT AND INTERPRETATION OF FIELD TESTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a - Detailed Guidelines</td>
</tr>
<tr>
<td>2b - User’s Manual</td>
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<table>
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<tr>
<th>TASK 3 - SOIL PROPERTY EVALUATION AND PROBABILISTIC MODELING</th>
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<tbody>
<tr>
<td>3a - Statistical Models</td>
</tr>
<tr>
<td>3b - Evaluation of In-Situ Tests</td>
</tr>
<tr>
<td>3c - Statistical Data Analysis</td>
</tr>
<tr>
<td>3d - Reliability-Based Correlation Models</td>
</tr>
<tr>
<td>3e - Reliability-Based Design Methods</td>
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<tr>
<th>TASK 4 - MODEL FOUNDATION LOAD TESTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a - Shafts in Sand, Cyclic Axial</td>
</tr>
<tr>
<td>4b* - Spread Foundations in Sand, Static Axial</td>
</tr>
<tr>
<td>4c* - Field Load Test Review, Cyclic</td>
</tr>
<tr>
<td>4d - Shafts in Clay, Cyclic Axial</td>
</tr>
<tr>
<td>4e - Shafts in Sand, Cyclic Lateral/Moment</td>
</tr>
<tr>
<td>4f - Shafts in Clay, Cyclic Lateral/Moment</td>
</tr>
<tr>
<td>4g - Shafts in Sand, Static Combined</td>
</tr>
<tr>
<td>4h - Shafts in Sand, Cyclic Combined</td>
</tr>
<tr>
<td>4i - Shafts in Clay, Static/Cyclic Combined</td>
</tr>
</tbody>
</table>

| TASK 7* - FIELD GRILLAGGE TESTING (ESEERCO) | completed (EL-6965) |

*Note: * indicates tasks that are ongoing or have been terminated.
Table 1.1
PROJECT CHART FOR RP1493 AS OF MAY 1995 (completed)

**TASK 5 - DESIGN PROCEDURES**

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<tr>
<td>5b*</td>
<td>CUFAD+ (1493-6)</td>
<td>completed (EL-6583-CCML)</td>
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<tr>
<td>5c*</td>
<td>Properties Manual (1493-6)</td>
<td>completed (EL-6800)</td>
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<tr>
<td>5d</td>
<td>Synthesis Design Manual</td>
<td>terminated</td>
</tr>
<tr>
<td>5e*</td>
<td>Brief Summary Report</td>
<td>completed (TR-105206)</td>
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<td>5f</td>
<td>FAD (1493-6, EPRI TLMRC)</td>
<td>in progress by EPRI</td>
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**TASK 6 - TECHNOLOGY TRANSFER**

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<tr>
<td>6b</td>
<td>Other Items Developed Specifically For or With EPRI</td>
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<tr>
<td>6c</td>
<td>Published Technical Papers Reporting Research Results</td>
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</tr>
<tr>
<td>6d</td>
<td>Technical Presentations Reporting Research Results</td>
<td>86</td>
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<tr>
<td>6e</td>
<td>Seminars and Short Courses Based on Research Results</td>
<td>121</td>
</tr>
<tr>
<td>6f</td>
<td>Published Technical Papers Resulting Indirectly from Research</td>
<td>19</td>
</tr>
<tr>
<td>6g</td>
<td>Contributions to Standards Committees</td>
<td>9</td>
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<tr>
<td>6h</td>
<td>Graduate Student Degrees Earned at Cornell Through RP1493</td>
<td>19</td>
</tr>
<tr>
<td>6i</td>
<td>Reports and Publications in Press</td>
<td>5</td>
</tr>
</tbody>
</table>

*sub-task or task added during research*
Section 2

ANALYTICAL MODELING (TASK 1)

Task 1 was developed originally to exploit existing, unique, numerical analysis and computer graphics capabilities that existed at Cornell University and to adapt them for use within the context of this project (Tasks 1a, b). Subsequent additions to this task (Tasks 1c, d) were to expand these efforts to other analytical issues. In general, the goals of this task were to: (a) provide analytical input into other project tasks where needed, (b) improve capabilities for modeling foundation behavior, (c) establish a variety of benchmark solutions, and (d) evaluate existing closed-form solutions.

The analytical tools developed in this task were used to assist Task 2 and Task 4 efforts. Task 2 is the load test manual, for which calibration and baseline studies were done to assist in field load test evaluation, as described elsewhere (A10). Task 4 is the model foundation load testing, for which much equipment and test chamber design was needed. Because of the ever-present problem of test chamber boundary influences, a suite of analyses was conducted that focused on optimizing the test chamber designs and the eventual matrix of testing variables. These results were utilized throughout all of Task 4 and are described elsewhere (A28 and various Task 4 reports).

The approaches to modeling foundation behavior were examined carefully, and numerous improvements were made. Improved algorithms were developed to implement non-linear soil-foundation interaction studies, and new models were developed to model soil-shaft interface behavior, including stick, slip, debonding, and reboning. All of this information was used to examine, model, and understand observed behavior more fully. Details are given in the report (A28).

Originally it was intended to provide a baseline of solutions to various drilled shaft foundation problems using sophisticated soil models. However, it became obvious that soil constitutive modeling is still within the research arena, and truly generalized models are still in the future. Accordingly, a comprehensive series of elastic-type benchmark solutions was developed for a wide range of boundary conditions. Although material property calibrations were done for rock sockets, the solutions are applicable for both soil and rock. More specifically, shafts were modeled in elastic media, with and without bond slip along the shaft-elastic medium interface, under both uplift and compression loading. Similar models were devel-
oped to address lateral, moment, and torsional loading modes. Details are given in the task reports (A11, A28).

Lastly, a comprehensive evaluation was done of existing analytical solutions for uplift, compression, and lateral/moment loading. Case histories were used to assess the model predictive capabilities using modern methods for evaluating load tests and soil properties developed within RP1493. A large number of specific recommendations, with detailed statistical quantification, are given for all axial and lateral/moment loading conditions (A27).
Section 3
LOAD TEST MANUAL (TASK 2)

As a guide for the originally proposed field load tests that were to be conducted in Task 4, and to assist any load test evaluation studies in Task 1 or other tasks, a comprehensive study was done to establish rational procedures for the conduct and interpretation of load tests on drilled shafts. The scope of the study was broad and self-contained, and the issues addressed included the following: (a) geotechnical data requirements, (b) load test planning and documentation, (c) equipment and hardware, (d) instrumentation, (e) data recording and presentation, (f) axial, lateral, moment, torsion, and combined load testing procedures, and (g) interpretation of all types of load test results.

Detailed and specific recommendations were developed for each of the items noted above, and new criteria were developed for the interpretation of load test results. These new criteria avoid the often arbitrary criteria used previously and utilize actual soil-foundation response as the primary criterion for the load test interpretations.

The task is reported in two parts. The first is a detailed manual containing extensive analyses and documentation (A10). The second is a streamlined user’s manual to provide quick access to the key elements of the test conduct and interpretation (A20). These documents were used extensively in later stages of the project.
Section 4

SOIL PROPERTY EVALUATION AND PROBABILISTIC MODELING (TASK 3)

This task initially was to include a significant component of field testing, but instead it evolved into a soil property assessment using available data. This redirection in effort focused on probabilistic modeling or, more accurately, proper quantitative assessment of property variability or uncertainty in the analysis and design process.

The research on this task evolved in several phases, with the first four focusing on efforts delineated in Figure 4-1. The initial study began to address inherent variability in the natural soil depositional environment and summarized existing data on property variability (A12). These data provided a baseline to understand inherent soil variability.

The second phase addressed variability in making in-situ measurements. This phase quantified, as a function of major in-situ test type, the primary variables in equipment, operator, and test uncertainty (A13).

The third phase considered the overall issues of uncertainty and variability in property evaluation (A14). General strategies were developed to address the problems, and major areas of uncertainty were delineated.

The fourth phase focused on model uncertainty in transforming an in-situ measurement into a “true” design soil property. Model variability, transformation reliability, measurement uncertainty, and other related issues were addressed in

![Diagram](image)

Figure 4-1. Uncertainty in Soil Property Estimates
establishing a general approach for quantifying the necessary transformation models (A22).

The fifth and final phase was to build on the previous efforts and to utilize all of the available field and laboratory information in developing a probability-based foundation analysis and design methodology that would incorporate uncertainty in soil property evaluation. The resulting design equations were to have the same "look and feel" as current deterministic equations, but they would have load and resistance factors that would be based on the various geotechnical uncertainties involved in the analysis/design process. For overall consistency, the loading side of the equations would be based on the ASCE Standard for Transmission Line Structure Loading. The specific focus of these efforts is toward drilled shaft foundations in drained and undrained axial and lateral/moment loading. Also included is spread foundations in uplift loading. This task resulted in the first general reliability-based design methodology for the foundations of transmission line structures (A30) that addresses both serviceability and ultimate limit states.
Section 5
MODEL FOUNDATION LOAD TESTING (TASK 4)

This task initially was to be a mix of laboratory-scale and field-scale foundation load tests. However, early in the project, the field testing was eliminated, and the laboratory testing was expanded. In the final project evolution, a broad testing matrix was developed, with specific focus on drilled shaft foundations and secondary interest in spread foundations in uplift.

The purposes of the laboratory testing program were to: (a) develop an experimental load test database, (b) compare analytical models of foundation behavior with experimental data, and (c) evaluate the effect of various parameters on the strength and deformation characteristics of common transmission line structure foundations under typical loading conditions. The principal parameters in this study included the following:

- Foundation type (drilled shaft [primarily] or spread foundations)
- Soil type (sand or clay)
- Loading direction (uplift, compression, lateral, moment, or combined)
- Loading type (static or cyclic)
- Foundation scale (50 mm, 75 mm, or 150 mm diameter with depth/diameter nominally from 3 to 9)
- Soil characteristics (loose, medium, or dense sand; very soft, soft, or medium clay)

Table 5-1 lists the studies completed under this task, along with the associated testing conditions. As indicated in this table, nine phases of testing and review were completed. Of these nine phases, one was a compilation of available field and laboratory test results; the other eight involved laboratory testing at Cornell University. In each study, the test results were related to full-scale behavior and design practice and, where applicable, recommendations were made for improved design methods.

The first phase of Task 4 (A6) investigated the static and cyclic axial loading of drilled shafts in sand and determined that the maximum displacement was an important predictor of the consequences of repeated loading. In the tests, cyclic creep occurred at displacements greater than about 1 mm and led to a progressive decrease in uplift capacity. Below this threshold, there was little decrease in capacity. The findings indicate that axial loads should be limited to achieve a safe level of cyclic loading.
Table 5-1
TESTING MATRIX

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<tr>
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<th>Soil Type</th>
<th>Loading Mode</th>
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<td>EL-5325</td>
<td>Laboratory</td>
<td>Drilled</td>
<td>Sand</td>
<td>Axial</td>
<td>S + C</td>
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<td>4b</td>
<td>TR-100220</td>
<td>Laboratory</td>
<td>Spread</td>
<td>Sand</td>
<td>Axial</td>
<td>S</td>
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<tr>
<td>4c</td>
<td>EL-5375</td>
<td>Data Review</td>
<td>Drilled</td>
<td>Various</td>
<td>Axial, Lateral</td>
<td>S + C</td>
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<td>Drilled</td>
<td>Clay</td>
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<td>S + C</td>
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<td>Drilled</td>
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</tbody>
</table>

a - S = static loading, C = cyclic loading

In the second phase (A21), 100-mm-wide model spread foundations (square and rectangular) were tested under static axial loads in sand of various densities and at various depths. Also studied were the effects of backfill versus native soil density. Tests were carried out to large displacements to define the entire load-displacement response, and recommendations were made relative to the advantages of various backfill compaction strategies.

The third phase (A7) was a review of existing field and laboratory studies of the cyclic axial and lateral loading of drilled shafts in various soil types. This study defined many response issues and was used as background for the subsequent laboratory testing phases.

The fourth phase (A19) involved the static and cyclic axial testing of drilled shafts in clay. This study first defined the applicable wind load magnitudes and directional characteristics. A simple and repeatable clay soil mixture was developed for use in all subsequent tests in cohesive soil. In addition to evaluating the load-displacement response of drilled shafts in overconsolidated clay, the tests investigated the Critical Level of Repeated Loading (CLRL) and defined the loss in strength that occurred over time as a result of cyclic loading.

In the fifth phase (A24), drilled shafts were tested under static and cyclic lateral and moment loads in sand. Major improvements were made to the materials handling system that enabled subsequent tests to be carried out considerably more
quickly and economically. The sixth phase (A23) included similar tests in clay. Both the fifth and sixth phase studies investigated the effects of the level of cyclic loading and the accumulations that occur during cyclic loading. Both studies determined that a hyperbolic model describes the overall load-displacement behavior well.

The seventh phase (A25) investigated the effects of static load inclination (combined loading) on drilled shafts in sand. Using 50-mm-diameter model shafts, the tests defined the changes in resistance at load angles ranging from axial uplift, through lateral, to axial compression. Various soil densities and shaft lengths were employed, and the interpretation of the results was consistent with previous tasks in this study, in which failure was defined using the Apparent Depth of Rotation (ADOR) criterion. The eighth phase (A26) extended the results from static loading by testing drilled shafts under inclined cyclic loading conditions in sand.

The ninth phase of testing (A29) investigated the response of drilled shafts under combined axial and lateral static and cyclic loads in clay. Various improvements were made to the testing system that resulted in considerably more consistent test conditions. As in previous tests, the study included a range of shaft lengths and loading conditions. The study defined the effects of load inclination on the response of foundations in clay. The seventh through ninth phases delineated the load inclination effects on foundation capacity, as well as the overall influence of repeated loading.

Taken as a whole, the nine phases of this task form the most comprehensive testing program on model drilled shaft and spread foundations available. Many hundreds of tests were completed under a wide variety of testing conditions, and they have led to significant improvements in the design of foundations for transmission line structures. In addition, all of the model test results were related to full-scale test behavior wherever possible. In all cases, the model and full-scale behavior was consistent.
Section 6
FIELD GRILLAGE TESTING (TASK 7)

In 1986, an opportunity presented itself when the Empire State Electric Energy Research Corporation (ESEERCO) agreed to co-fund a task on field testing of existing grillage foundations. These grillages constitute a substantial fraction of in-place foundations for lattice transmission line towers, but much of their behavior under load is not understood well.

In this study, eight foundations from three lattice towers, in place since 1929, 1947, and 1958, were tested to failure in uplift. The grillage field sites were explored extensively with in-situ tests, including standard penetration, cone penetration, pressuremeter, borehole shear, drive cone, and dilatometer tests. Laboratory classification and strength tests also were conducted to provide full geotechnical characterization.

Testing of the grillages was done following the general guidelines given in Task 2. All tests were brought to very large displacements to characterize fully the complete load-displacement response. After testing, all grillages were exhumed to assess the overall condition of the galvanized steel members and all connections. Remarkably, all were in good condition.

The test results were evaluated comprehensively, and it was shown that the general criteria given previously (A1, A3, A21) described the results well. Guidelines for capacity assessment were improved, and new criteria were suggested for evaluating the overall load-displacement response. Details are given in the EPRI/ESEERCO report (A18).
Section 7

DESIGN PROCEDURES (TASK 5) AND TECHNOLOGY TRANSFER (TASK 6)

During the initial formulation of the project, it was planned to integrate all of the research results into a Synthesis Design Manual, as noted in Section 1. However, this task was eliminated in 1991 because of budgetary issues. However, design recommendations have been made in each EPRI report, and the reader is directed toward the report listing in the Appendix. Table 1-1 lists the specific subjects for which design recommendations have been made.

Outside of RP1493-4, additional design criteria have been developed within RP1493-6 that are synergistic with this study. Specifically, a Properties Manual has been developed (A17) to assist designers in selecting soil properties for design. In addition, much of the technology developed in RP1493-4 has been coded into the CUFAD and CUFAD+ software (A9, A15, A16). Further developments in progress are evolving these software modules into FAD (Foundation Analysis and Design), which also will incorporate most of the key task and sub-task results. This integration is illustrated in Figure 1-1.

On this project, technology transfer has been pursued vigorously. In Table 1-1, under Task 6, the specifics are enumerated, and Appendix A provides a complete listing as of this writing. As noted, the project output has been very substantial. This output will continue into the future, when EPRI funding no longer exists, because it is necessary to get this information into the hands of foundation design engineers.
Section 8

CONCLUDING COMMENTS

Research Project RF1493 has met and exceeded all initial goals, even after numerous significant changes during the project. Tremendous advances have been made, and our knowledge of soil and foundation behavior has improved remarkably. Figure 1-1 outlines the general areas involved, while Table 1-1 lists the specific areas of accomplishment. To put these issues in perspective, the resulting EPRI reports alone contain over 7,600 pages of text. As of this writing, plans are that the majority of these results will be incorporated into a single software module, FAD (Foundation Analysis and Design).
Appendix A

TECHNOLOGY TRANSFER LISTING AS OF MAY 1995

A. Reports Published by EPRI


B. Other Items Developed Specifically For or With EPRI

1. FH Kulhawy, TD O'Rourke, JF Beech & HL Davidson Seminar Notes on Foundation Design for Transmission Structures EPRI, Palo Alto, Apr 1982

2. FH Kulhawy w. TD O'Rourke & HL Davidson "Foundation Engineering for Transmission Line Structures" Videotape Series EPRI, Palo Alto, Dec 1982, 7 hrs


5. "Study Here Could Save Utilities $1.6 Billion" Cornell Chronicle 30 May 1985


10. FH Kulhawy & CH Trautmann "Improved Foundations for Transmission Line Structures" 15-minute videotape filmed at Cornell Univ. for EPRI, May 1990 (To be shown at CIGRE and elsewhere)


C. Published Technical Papers Reporting Research Results


64. KJ McManus & FH Kulhawy "Cyclic Axial Loading of Drilled Shafts in Cohesive Soil" J. Geotech. Eng. (ASCE) 120(9), Sep 1994, 1481-1497.


D. Technical Presentations Reporting Research Results


4. FH Kulhawy "Limiting Tip and Side Resistance - Fact or Fallacy" ASCE Fall Meeting, San Francisco, Oct 1984

6. FH Kulhawy "Drilled Shaft Foundations Under Axial Load" Boston Society of Civil Engineers Section - ASCE, Boston, Feb 1985
11. TD O'Rourke & FH Kulhawy "Uplift Behavior of Anchor Foundations in Soil - An Overview" ASCE Fall Meeting, Detroit, Oct 1985
14. CH Trautmann "Spread Foundations in Uplift: Experimental Study" ASCE Spring Meeting, Atlantic City, Apr 1987
15. KL Gunsallus "Numerical Simulation of Behavior of Drilled Shaft Foundations" ASCE Spring Meeting, Atlantic City, Apr 1987
19. FH Kulhawy "Transmission Line Structure Foundation Research at Cornell University" EPRI Task Force Meeting, Montreal, Sep 1987
22. FH Kulhawy "Tension Behavior of Foundations in Soil" (Cross-Canada Lecture) Vancouver, Edmonton, Regina, Winnipeg & Toronto, Feb 1988
23. FH Kulhawy "Tension Behavior of Foundations in Soil" Univ. of Sydney, Sydney, Mar 1988
26. FH Kulhawy "Tension Behavior of Foundations in Soil" (Cross-Canada Lecture) Ottawa, Montreal, Quebec, Halifax, St. Johns & Fredericton, Apr/May 1988
36. FH Kulhawy "Recent Developments in Interactive Computer Graphics for 3-D Nonlinear Geotechnical FEM Analysis" ASCE Fall Meeting, St. Louis, Oct 1988
48. CH Trautmann "Use of Knowledge-Based Front Ends in Civil Engineering Design Programs" 7th Natl. Conf. on Microcomputers in Civil Eng., Orlando, Nov 1989
49. CH Trautmann "Transmission Line Structure Foundation Design Software & Rule-Based Advisor for Input Data" 1st Conf. on Advanced Computer Technology for Power Industry, Scottsdale, Dec 1989
50. PW Mayne "Direct and Indirect Determinations of $K_o$ in Clays" Transportation Research Board, Washington, Jan 1990
51. FH Kulhawy "Geotechnical Issues Influencing Installation of Foundations for Transmission Line Structures" IEEE PES Winter Meeting, Atlanta, Feb 1990
54. FH Kulhawy "Axial Behavior of Drilled Shafts" Geosyntec Consultants Distinguished Lecture #8, Atlanta, Mar 1991


58. FH Kulhawy "Fifteen+ Years of Model Foundation Testing in Large Chambers" Invited Lead Lecture, 1st Intl. Symp. on Calibration Chamber Testing, Potsdam, Jun 1991

59. PW Mayne "Calibration Chamber Boundary Effects Correction for CPT Data" 1st Intl. Symp. on Calibration Chamber Testing, Potsdam, Jun 1991

60. FH Kulhawy "Relative Density, SPT & CPT Interrelationships" 1st Intl. Symp. on Calibration Chamber Testing, Potsdam, Jun 1991


66. FH Kulhawy "Foundations Research at Cornell" EPRI Task Force Meeting, Monterey, Jan 1992


68. FH Kulhawy "On the Evaluation of Static Soil Properties" Invited Theme Lecture, ASCE Specialty Conf. on Stability & Performance of Slopes & Embankments-II, Berkeley, Jun 1992

69. FH Kulhawy "Some Thoughts on Evaluation of Undrained Shear Strength for Design" Peter Wroth Memorial Symposium, Oxford, Jul 1992


71. FH Kulhawy "Evaluation of Static Soil Properties in Geotechnical Design Practice" Maunsell Fellow Lecture, Inst. of Engineers, Hong Kong, Feb 1993

72. FH Kulhawy "Foundation Engineering Research at Cornell" Univ. of Hong Kong, Mar 1993

73. FH Kulhawy "On the Evaluation of Static Soil Properties" Italian Geotech. Society, Milan, Apr 1993


77. FH Kulhawy (by A Hirany) "Drilled Shaft Side Resistance in Clay Soil to Rock" ASCE Fall Meeting, Dallas, Oct 1993

78. FH Kulhawy "On the Evaluation of Static Soil Properties" Institution of Professional Engineers New Zealand-Geomechanics Group, Wellington, Nov 1993

79. FH Kulhawy "On the Evaluation of Static Soil Properties" Univ. of Canterbury, Christchurch (N.Z.), Nov 1993

80. FH Kulhawy "On the Evaluation of Static Soil Properties" Univ. of Auckland, Auckland (N.Z.), Nov 1993

81. FH Kulhawy "Fifteen+ Years of Model Foundation Testing in Large Chambers" FHWA Workshop on Micropiles, Washington, Mar 1994

82. FH Kulhawy "Uplift Load-Displacement Behavior of Grillage Foundations" ASCE Settlement '94 Conf., College Station, Jun 1994


86. FH Kulhawy "Reliability Issues in Geotechnical Engineering & LRFD Codes" Transportation Research Board, Washington, Jan 1995

E. Seminars and Short Courses Based on Research Results


2. FH Kulhawy "Foundations for Transmission Line Structures" Oregon State Univ., Corvallis, Jan 1982


4. FH Kulhawy "Design of Foundations in Rock" Univ. of Texas, Austin, Apr 1983

5. FH Kulhawy "Design of Drilled Shafts for Axial Loads" & "Design Testing" ADSC Drilled Foundation Seminar, Salt Lake City, Sep 1983


16. FH Kulhawy "Recent Developments in Design of Deep Foundations for Axial Loads" Corporate Seminar for CH2M-Hill, Portland (OR), Sep 1984
17. FH Kulhawy "Recent Developments in Design of Deep Foundations for Axial Loads" Corporate Seminar for Chen & Assoc., Denver, Feb 1985
20. JP Turner "Drained Uplift Capacity of Drilled Shafts Subjected to Repeated Axial Loads" Univ. of California, Berkeley, Mar 1985
23. FH Kulhawy "Behavior of Anchor Foundations" Syracuse Univ., Syracuse, Apr 1985
24. FH Kulhawy "Design of Drilled Shafts for Axial Loads" & "Evaluation of Load Tests" ADSC Drilled Foundation Seminar, Dallas, Apr 1985
25. CH Trautmann "Engineering Geology for Site Evaluations" Amherst College, Amherst, Apr 1985
29. FH Kulhawy "Foundation Engineering for Transmission Line Structures" Univ. of Cambridge, Cambridge, Oct 1985
30. FH Kulhawy "Design of Foundations in Rock" Univ. of Cambridge, Cambridge, Oct 1985
31. FH Kulhawy "Foundation Engineering for Transmission Line Structures" Univ. of Sheffield, Sheffield, Oct 1985
36. FH Kulhawy "Geotechnical Engineering for Transmission Line Structures" Electricity Commission of New South Wales, Sydney, Jan 1986
37. FH Kulhawy "Recent Advances in Foundation Engineering for Transmission Line Structures" Univ. of Sydney, Sydney, Jan 1986
38. FH Kulhawy "Modern Concepts in Foundation Engineering" Univ. of Hawaii, Honolulu, Spring 1986
39. FH Kulhawy "Foundation Engineering for Transmission Line Structures" Hawaii Section-ASCE, Honolulu, Apr 1986
40. CH Trautmann "Improved Methods of Foundation Design for Transmission Line Structures" Northeast Transmission Group, Toronto, May 1986
41. FH Kulhawy "Subsurface Engineering" Hawaii Inst. of Geophysics, Honolulu, May 1986
43. FH Kulhawy "Design of Drilled Shafts for Axial Loads" ADSC Drilled Foundation Seminar, Indianapolis, Jun 1986
46. FH Kulhawy & CH Trautmann "Foundation Design for Transmission Line Structures" week-long EPRI short course, Pittsburgh, Jul 1986
47. FH Kulhawy "Foundation Engineering for Transmission Line Structures" Clarkson Univ., Potsdam, Sep 1986
50. FH Kulhawy "CUFAD Computer Program Demonstration" EPRI TLWorkstation Seminar, Dallas, May 1987
51. FH Kulhawy "Uplift Behavior of Shallow Soil Anchors" Keynote Address, Seminar on Foundations in Tension, Boston, Jun 1987


56. FH Kulhawy "CUFAD Computer Program Demonstration" Virginia Polytechnic Inst. & State Univ., Blacksburg, Oct 1987

57. FH Kulhawy "Uplift Behavior of Shallow Soil Anchors" Keynote Address, Seminar on Tieback & Anchor Systems, Atlanta, Oct 1987

58. CH Trautmann "In-Situ Soil Testing for Exploration of Transmission Line Structure Sites" Fachhochschule Muenchen, Munich, Dec 1987

59. FH Kulhawy "Design of Drilled Shaft Foundations" one-day short course, Univ. of Sydney, Sydney, Mar 1988

60. PW Mayne "Direct & Indirect Measurements of In-Situ K_o by Self-Boring Pressuremeter, Dilatometer and Piezcone" Intl. Symp. on Penetration Testing, Orlando, Mar 1988

61. PW Mayne "Penetration Pore Water Pressures & Horizontal Stresses in Clay by Dilatometer" Intl. Symp. on Penetration Testing, Orlando, Mar 1988

62. PW Mayne "Statistical Correlations of Preconsolidation Stresses in Clay by In-Situ Tests" Intl. Symp. on Penetration Testing, Orlando, Mar 1988


65. FH Kulhawy "Foundations for Transmission Line Structures" 2.5 day short course, Western Area Power Administration, Golden, Jun 1988


68. CH Trautmann "New Developments in Design of Foundations for Transmission Line Structures" Technische Universitaet Muenchen, Munich, Jul 1988

69. FH Kulhawy & CH Trautmann "Foundation Engineering for Transmission Line Structures" 3.5 day EPRI short course, Annapolis, Oct 1988


74. FH Kulhawy & CH Trautmann "Foundation Engineering for Transmission Line Structures" 3.5 day EPRI short course, Palo Alto, Oct 1989
75. PW Mayne "Lateral Load Behavior of Rigid Drilled Shafts in Clay" Georgia Tech Atlanta, Jan 1990
76. FH Kulhawy "Design of Foundations On and In Rock" Univ. of Minnesota, Minneapolis, Feb 1990
77. PW Mayne "Behavior of Laterally Loaded Model Drilled Shafts in Clay" Northeastern Univ., Boston, Feb 1990
78. PW Mayne "Lateral Load Behavior of Rigid Drilled Shafts in Clay" Univ. of Texas, San Antonio, Mar 1990
80. PW Mayne "Lateral Load Response of Drilled Shafts in Clay" Purdue Univ., West Lafayette, Mar 1990
84. PW Mayne "Lateral Load Response of Drilled Shafts in Clay" Univ. of Illinois, Urbana, Apr 1990
86. FH Kulhawy & CH Trautmann "Foundation Engineering for Transmission Line Structures" 4 day EPRI short course, Haslet, Apr/May 1990
87. FH Kulhawy "Design of Drilled Shafts for Axial Loads" & "Load Test Conduct & Interpretation" ADSC Drilled Foundation Seminar, Detroit, Oct 1990
89. FH Kulhawy "Design of Drilled Shafts for Axial Loads" & "Load Test Conduct & Interpretation" ADSC Drilled Foundation Seminar, Kansas City, Nov 1990
90. HE Stewart "Field Evaluation of Grillage Foundation Uplift Capacity" Univ. of Mass., Amherst, Nov 1990
91. FH Kulhawy & CH Trautmann "Foundation Engineering for Transmission Line Structures" 4 day EPRI short course, Atlanta, Mar 1991
93. FH Kulhawy "Axial Behavior of Drilled Shafts" Georgia Tech, Atlanta, May 1991
94. FH Kulhawy "CUFAD & CUFAD+ Computer Demonstrations" EPRI TLWorkstation Northeast & Central Users' Groups Seminar, Syracuse, Sep 1991
95. FH Kulhawy "Design of Drilled Shafts for Axial Loads" & "Load Test Conduct & Interpretation" ADSC Drilled Foundation Seminar, Pittsburgh, Sep 1991
96. FH Kulhawy "Design of Drilled Shafts for Axial Loads" & "Load Test Conduct & Interpretation" ADSC Drilled Foundation Seminar, Phoenix, Oct 1991
100. FH Kulhawy "Reliability Methods in Foundation Design" Workshop on Reliability Methods for Risk Mitigation in Geotech. Eng., Irvine (CA), Jul 1992
101. FH Kulhawy & CH Trautmann "Foundation Engineering for Transmission Line Structures" 4 day EPRI short course, Dallas, Aug 1992
103. FH Kulhawy "Site Investigation for Transmission Line Structures" NY State Electric & Gas, Binghamton, Oct 1992
104. FH Kulhawy "Foundations for Structures in Karstic Limerock in South Florida" Univ. of Hong Kong, Jan 1993
105. FH Kulhawy "Modern Topics in Foundation Engineering, with Emphasis on Drilled Shafts" 2.5 day short course, Hong Kong Inst. of Engineers/Univ. of Hong Kong, Mar 1993
106. FH Kulhawy "Basic Principles of Design & Construction of Drilled Shafts" Univ. of Hawaii, Honolulu, Mar 1993
107. FH Kulhawy "Estimation of Soil Properties for Foundation Design" 1 day short course, Univ. of Sydney, Jun 1993
108. FH Kulhawy "Foundation Engineering for Electrical Transmission Line Structures" 70% of 5 day short course, Univ. of Queensland, Brisbane, Jul 1993
109. FH Kulhawy "Drilled Shaft Foundations" 2 day short course, Univ. of Queensland, Brisbane, Jul 1993
110. FH Kulhawy & CH Trautmann "Foundation Engineering for Transmission Line Structures" 4 day EPRI short course, Dallas, Mar 1994
112. FH Kulhawy "Future Trends in Deep Foundation Design Concepts" Univ. of New Mexico, Albuquerque, May 1994
114. FH Kulhawy "Estimation of Soil Properties for Foundation Design" 1 day short course, Univ. of Washington, Seattle, Nov 1994
115. FH Kulhawy "Drilled Shaft Foundations" 2 day short course, Univ. of Hawaii, Honolulu, Nov 1994
116. "Drilled Shaft Foundations" 2.5 day short course (12 lectures), Univ. of Hong Kong/Hong Kong Institution of Engineers, Mar 1995
117. "Uncertainty in Geotechnical Property Evaluation" in 1 day short course on Dealing with Uncertainty & Risk in Geotech. Eng., Univ. of Hong Kong/Hong Kong Institution of Engineers, Apr 1995
118. "Lateral/Moment Loading Behavior of Drilled Shafts" Polytechnic Univ., Brooklyn, Apr 1995
120. "Foundation Eng. for Transmission Line Structures" Univ. Maryland, College Park, Apr 1995
121. "Foundation Eng. for Transmission Line Structures" 4 day EPRI short course (18 lectures), Binghamton NY, May 1995

F. Published Technical Papers Resulting Indirectly From Research


G. Contributions to Standards Committees


5. FH Kulhawy "Drilled Shaft Foundations" (revision) Transmission Line Structure Foundation Standards Committee, ASCE, New York


7. FH Kulhawy "Anchors" (revision) Transmission Line Structure Foundation Standards Committee, ASCE, New York


9. FH Kulhawy "Various Contributions" Drilled Shaft Standards Committee, ASCE, New York

A-18
H. Graduate Student Degrees Earned at Cornell Through RP 1493

1. Christina V. Stas - MS, May 1983
2. Kent A. Pease - MS, Jan 1984
3. J. Francis Callanan - MS, Aug 1984
4. John P. Turner - PhD, Jan 1986
5. Mary J. Spry - MS, Jan 1986
6. John F. Beech - PhD, May 1986
7. Costakis N. Nicolaides - MS, Aug 1986
8. Craig J. Orchant - MS, Jan 1987
10. Anwar Hirany - PhD, May 1988
11. Kevin J. McManus - PhD, Jan 1989
12. Paul W. Mayne - PhD, Jan 1991
13. Sherif W. Agaiby - PhD, Jan 1991
15. Stevan D. Vidić - MS, Aug 1991
16. Yit-Jin Chen - PhD, Jan 1993
17. Stevan D. Vidić - PhD, Aug 1993
18. Nam Jun Cho - PhD, Jan 1995
19. Kok Kwang Phoon - PhD, May 1995

I. Technical Papers In Press or Review


2. SW Agaiby, FH Kulhawy & CH Trautmann "On Large-Scale Model Testing of Laterally Loaded Drilled Shafts in Sand" (in review)

3. PW Mayne, FH Kulhawy & CH Trautmann "Laboratory Modeling of Laterally-Loaded Drilled Shafts in Clay" (in review)

4. FH Kulhawy "Some Modeling Issues in Foundation Engineering" (in review)

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