Performance of Laterally Loaded Drilled Shafts in Rock

I. Problem Statement Number
To be determined by TRB

II. Research Problem Statement

Drilled shaft foundations are widely used for bridge foundations where large axial and lateral loads are to be resisted. Where rock bearing strata are present, individual drilled shafts are capable of supporting very large loads. Lateral load capacity can be substantial because of their large diameter and superior moment resistance. Drilled shafts are particularly well suited to conditions where scour, wind loads, vessel collision loads, or high seismic hazards are present. Drilled shafts are often installed into rock so that the rock socket provides the lateral and overturning resistance needed to support large lateral loadings.

Engineers confronted with the problem of designing drilled shafts for lateral loading most often use a computer solution which models the soil as a series of nonlinear springs, i.e., *p-y* curves. This approach is well suited to the problem of laterally loaded drilled shafts and is a relatively mature technology. Computer programs are available which are robust and numerically efficient, and can model the nonlinearity in the response of the soil and the nonlinearity in the flexural response of the reinforced concrete.

The difficulty for drilled shafts in rock lies with the ability to characterize the rock for this purpose, and incorporate a *p-y* model for rock into the design which is considered reliable and accurate. The *p-y* models used in design should be based on empirical correlations developed from realistic, full scale load tests. For drilled shafts in rock, the test data used to develop the most widely used correlations are extremely limited and may not be reliable for a majority of projects in the U.S.

A recent NCHRP synthesis report (20-5) "Use of Rock-Socketed Drilled Shafts for Highway Structure Foundations" (currently in final draft form) included an extensive survey of practice from transportation agencies and noted the following:

1) ***existing published criteria for p-y curves in rock are based on a very limited number (two) of full-scale field load tests;***
2) ***recommendations for selecting values of input parameters required by the published criteria are vague and unsubstantiated by broad experience,***
3) ***the p-y method of analysis is being used extensively despite these sources of uncertainty.***

It is therefore concluded that research is needed and should be undertaken with the objective of developing improved criteria for p-y curves in rock. The research should include full-scale field load tests on instrumented shafts, much in the same way that earlier studies focused on the same purpose for deep foundations in soil.

Where the design of a drilled shaft is governed by lateral loading, it is often the case that engineers (understandably) are extremely conservative in estimating the lateral capacity of the rock socket. As a result, contractors may be forced to drill into extremely hard rock to unnecessarily great depths, resulting in increased costs and potential delays and claims associated with difficult rock drilling conditions.

Another consideration is the move toward reliability-based design in the AASHTO LRFD Bridge Design Specifications. Although some work has been done toward calibration of axial design methods, there has been no research in development of a reliability based approach toward lateral loading for drilled shafts in rock.

Some structural issues affect drilled shafts in rock. Because of the high rate of load transfer and the large moment gradient with respect to depth, computed shear values near the top of a rock socket can be very high. Codes may require additional shear reinforcing for such instances. Given that the concrete in such a case is confined within the rock socket, the additional transverse reinforcement for this computed shear may be unnecessary and can be a construction problem during concrete placement. The confinement provided by a rock socket likely has an effect on the bending strength as well, if the bond at the shaft/rock interface engages a portion of the rock during flexure.

The key for improving the economy and reliability of drilled foundations in rock is to develop models which:

1) are based on realistic test data from carefully performed and well instrumented large scale load tests,
2) incorporate the nonlinear effects of flexure in a reinforced concrete drilled shaft,
3) address a wide range of rock types and conditions that might be encountered across the U.S.,
4) use correlations to measurable properties that can be obtained from routine site investigations in rock.

There are some test data available from site-specific load tests on bridge projects around the country. Many of these tests may have limited instrumentation or geotechnical data, or may not have included loads to a sufficiently large magnitude to actually mobilize significant lateral resistance from the rock. Some tests have been performed using the lateral O-cell or lateral Statnamic devices. In order to improve practice and also advance the state of practice toward reliability-based design, it is important that test data from a large number of load tests across a wide range of conditions should be examined and evaluated.

III. Research Objective

The overall objective of the proposed research is to develop improved models for analysis and design of laterally loaded drilled shafts in rock. The models should be readily implemented in practice, should cover a wide range of rock conditions, and should be demonstrated to be reliable and effective through comparisons with full scale load tests. In order to accomplish this overall objective, several specific tasks are necessary.

Task 1. Assemble and Evaluate Available Load Test Data. This task includes assembly of a comprehensive data set of useful lateral load tests of drilled shafts in rock. The criteria for selection should include:

- load test data must be sufficiently well instrumented that at least the deflected shape of the shaft can be defined,
- the nonlinear behavior of the shaft (including casing, if used) must be evaluated so that the response of the rock is not obscured by uncertainties in the shaft behavior,
- the mobilization of significant lateral resistance in the rock; if overburden soils are present, this condition must not obscure or make uncertain, the actual load supported by the rock,
- test sites that have sufficient site investigation at the immediate test location and that the test results can be correlated with quantifiable rock properties.

While it is not considered feasible to directly derive *p-y* curves from load tests on reinforced concrete shafts in the same way that is possible with linear elastic steel piles, the evaluation of available load test data should include a comparison of the test results with some form of nonlinear load transfer between shaft and rock.

Task 2. Identify Gaps in Data and Models and Develop a Plan for Additional Load Testing. It is anticipated that the available data will include significant gaps between the data needed to accomplish the research objective and the load test data identified and assembled in Task 1. The research team should also perform an evaluation of State Agencies' perceptions of the most common types of problems and rock types encountered, and should perform sensitivity studies to evaluate the importance of various parameters. An assessment of the state of knowledge relating to structural design issues should be performed in order to address the effect of confinement within the rock socket on the structural behavior.

Task 3. Develop or Refine Design Methodology. Based on the results of Tasks 1 and 2, improved design methodologies should be developed and proposed.

Task 4. Perform Additional Load Tests. This task includes development of a plan to address shortcomings in the experimental data identified in Task 2, and needed research to address structural issues. It is anticipated that the research team would develop a cost-effective approach to additional testing. Field testing would be performed by using the most feasible and economical combination of either separately contracted load tests or tests performed in coordination with state agencies or industrial partners in conjunction with ongoing projects. A sufficient number of load tests should be performed to develop modeling criteria that is currently lacking for typical rock conditions.

Task 5. Finalize Design Methodology. The additional test data should be used to validate and/or refine the proposed design methodology and provide specific recommendations that meet the project objectives.

<u>Task 6. Final Report</u>. The results of the research shall be incorporated into a final project report, which shall include recommendations for implementation of the research findings into practice.

IV. Estimate of Problem Funding and Research Period

The cost of this project is estimated to be approximately $500,000 spread over a 3-4 year period. All costs associated with drilled shaft construction and subsurface investigation and testing are not included in the estimated budget. Analysis, interpretation and research will be covered by the NCHRP Project funds. Costs of drilled shaft construction, load testing and subsurface investigations will be covered by a combination of NCHRP funds and the support of State agencies and Industry partners. It is anticipated that NCHRP funds may be used to provide instrumentation free of charge to States to encourage State participation.

VI. Urgency, Payoff Potential and Implementation

Recent years have seen a great increase in the use of drilled shafts in rock because of increased considerations of extreme event loading conditions including scour, seismic, vessel impact, and wind. For major bridge projects, 20 to 30 percent or more of the costs of the structure may be associated with substructure costs and rock excavation is often a substantial portion of those costs. Because the foundation construction is typically on the critical path for the schedule, delays or costs associated with rock drilling can often multiply the impact many times over. Improved understanding of the behavior of rock sockets will minimize the potential for unnecessary delays due to excessive rock excavation.

The proposed research is consistent with the grand challenges for bridge engineering as identified by the AASHTO subcommittee on bridges and structures. Improved design of drilled shaft rock sockets can extend service life by strengthening foundations against scour, earthquake, and impact damage, since these are conditions directly related to the need for rock sockets with drilled shaft foundations. The research will optimize structural systems by furthering the development of reliability-based engineering design for laterally loaded drilled shafts. This subject has not been directly addressed by other research efforts aimed at calibrating LRFD design methodology for foundations. The research will assist in accelerating bridge construction by reducing the need for costly rock excavation and minimizing the risk of delays on the critical path of the construction schedule. The research will advance the AASHTO specifications by providing a data base of lateral load tests in rock and improving design methodology for identification of load distribution methods for foundations.

The user community includes all transportation agencies for highway, mass transit, railroad, airport and marine facilities.

Implementation
The results of this project can be implemented through the following vehicles:

- NCHRP reports
- National Highway Institute training courses (existing and new),
- FHWA pile load test database.
- Computer programs (public and private sector).
- Changes to the AASHTO design code.

VII. Organization Developing the Problem Statement

TRB Committee AFS30: Foundations for Bridges and other Structures
Contact Persons:

Jan L. Six, P.E.
Senior Geotechnical Engineer
Bridge Engineering Section
355 Capitol St., Room 301
Salem, OR 97301-3871
Ph. 503-986-3377
Fax 503-986-3407
Email: jan.l.six@odot.state.or.us

Mark J. Morvant, P.E.
Associate Director, Technology Transfer
Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808
Ph. 225-767-9124
Fax. 225-767-9159
Email: mmorvant@dotd.louisiana.gov

VIII. Problem Monitor

To be determined by TRB

IX. Date and Submitted by:

Oregon Department of Transportation and Development

Jan L. Six, P.E.
Senior Geotechnical Engineer
Bridge Engineering Section
355 Capitol St., Room 301
Salem, OR 97301-3871
Ph. 503-986-3377
Fax 503-986-3407
Email: jan.l.six@odot.state.or.us

TRB Committee AFS30: Foundations for Bridges and other Structures