ADOT ARIZONA DEPARTMENT OF TRANSPORTATION
RESEARCH CENTER
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RESEARCH RESULTS DIGEST

CALIBRATING SIDE RESISTANCE FACTORS OF DRILLED SHAFTS

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Drilled shafts have proven to be an excellent cost-effective deep foundation solution for bridge design that has been used in Arizona for many years. Over the past decade, the design of drilled shafts has shifted from an allowable stress method to Load and Resistance Factor Design (LRFD). Use of the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design specifications is mandatory for all federally funded projects in Arizona, and ADOT employs the LRFD method for all bridges. The seventh (2012) and eighth (2014) editions of the AASHTO LRFD Bridge Design Specifications (referred to as AASHTO 2012 and 2014, respectively) recommend the use of side resistance and tip resistance factors that range from 0.40 to 0.60 to determine the limit state of axial resistance of drilled shafts, depending on the soil conditions and safety requirements. The limit state is a condition of a structure beyond which it no longer fulfills the relevant design criteria. However, load tests performed in Arizona indicate that these AASHTO recommendations for resistance factors may be overly conservative for drilled shafts in Arizona soils, resulting in foundations that are deeper and costlier than necessary.

RESEARCH OBJECTIVE AND SCOPE

This research intended to calibrate the resistance factors and identify opportunities to improve reliable and cost-effective drilled-shaft design guidelines appropriate for Arizona, based on results from drilled-shaft load tests. The research scope comprised the following tasks:

- Collect and interpret results from drilled-shaft load tests and corresponding geotechnical site investigations in Arizona and other locations with soils similar to Arizona.
- Develop a matrix with all collected and interpreted data.
- Determine the predicted and measured axial resistance of drilled shafts at the limit state using the data from the load test and geotechnical site investigations and following both AASHTO 2012 and AASHTO 2014 guidelines.
- Calibrate the resistance factors, using the predicted and measured axial resistance of the drilled shafts and following the statistical analysis and LRFD methodology prescribed in the AASHTO guidelines and related literature.
- Analyze the impact of the different AASHTO guidelines and newly calibrated resistance factors on five Arizona bridge design projects.
- Determine potential cost savings for the different guidelines and resistance factors.

RESEARCH RESULTS

A matrix was developed with geotechnical site investigation data and load test data. Geotechnical site investigation data were collected from 67 project reports: 57 from Arizona, four from Nevada, three from California, and three from New Mexico. Boring logs and laboratory testing results—including soil classifications, standard penetration test (SPT) N-values for the different soil types, unconfined compressive strength (UCS) and rock quality designation (RQD) values for rock, groundwater levels, and a general interpretation of the subsurface conditions—were collected from each project report and summarized.

Load test data (including additional geotechnical site investigation data) were collected from 70 project reports: eight from Arizona, two from California, 11 from Colorado, five from New Mexico, and 44 from Nevada. The drilled-shaft load data were collected, indexed, and populated in an electronic format (Microsoft Excel file). The load test data required processing and, in many cases, significant extrapolation to obtain the measured axial resistance at the limit state, which is defined as the resistance at a settlement equal to 5 percent of the shaft diameter, or at the onset of plunging failure.

The axial resistance was predicted following both AASHTO 2012 and AASHTO 2014 guidelines and using idealized soil profiles, which consider as input variables the soil type (cohesive or cohesionless), SPT N-value, unit weight, cementation conditions, and undrained shear strength. The AASHTO 2012 and 2014 procedures for calculating the axial resistance are similar, except for the method used to calculate the side resistance in cohesionless soils. In many of the soil profiles in this study (particularly for the load tests from Nevada), cemented soils occur, which typically result in SPT refusal. The AASHTO guidelines are not conclusive on how to determine the side and tip resistance for cemented soils. This study investigated different methods to deal with cemented soils:

- Method A: Cemented soil was treated the same way as its parent soil material (cohesive or cohesionless), following AASHTO guidelines, with the SPT N-value limited to 50.
- Methods B1 and B2: Heavily cemented soils, or caliche (only in Nevada), were treated as rock, following AASHTO guidelines, in which the unit side resistance was determined from the unconfined compressive strength.

The calibrations were performed using different data sets:

- Data set 1: Arizona data only (seven load tests)
- Data set 2: All data from Arizona, Nevada, and New Mexico (53 load tests)
- Data set 3: Data selected by ADOT to exclude profiles with large amount (more than 10 percent) of strongly cemented caliche (41 load tests)

For the different methods and data sets, determinations were made for the predicted and measured axial resistance, bias factor (i.e., the average ratio between measured and predicted resistance), and coefficient of variation. The bias factor and corresponding coefficient of variation were then used to determine the newly calibrated resistance factors using Monte-Carlo analysis. The scope for the LRFD calibration was limited to cohesive or cohesionless soils. Excluded from the analysis were load tests for drilled shafts predominantly in rock or intermediate granular materials

predominantly in rock or intermediate granular materials (IGM).

The LRFD calibration results confirmed that the design methodology for drilled shafts in Arizona is conservative when following the AASHTO guidelines (both 2012 and 2014) and systematically under-predicts the axial capacity. However, the obtained bias factor, coefficent of variation, and resulting resistance factors varied significantly depending on the selected method and data set.

While the seven load tests from Arizona (dataset 1) were not enough to draw statistically solid conclusions, they showed average bias factors ranging from 1.84 to 2.18, with a high coefficient of variation and resulting resistance factors exceeding 1.0 in all cases. Using all data (dataset 2) or the data selected by ADOT (dataset 3) still showed very high average bias factors when cemented materials were treated as their parent material (method A), with resistance factors ranging from 0.74 to 0.86. The high bias factors could be attributed in large part to the relatively large proportion of soil profiles showing SPT blow count values exceeding 50, including refusal.

Since the AASHTO guidelines limit the SPT blow count to 50, the actual resistance of the soil is structurally underestimated when the SPT value is 50 or greater (including refusal). It was shown that the bias factor increased with increasing caliche content. Methods B1 and B2, in which heavily cemented material was treated as rock, resulted in significantly lower bias factors—with average bias values ranging from 1.41 to 1.66, the coefficient of variation ranging from 0.37 to 0.41, and resistance factors ranging from 0.49 to 0.65.

The potential impact of the different AASHTO guidelines and different resistance factors was investigated through a comparative analysis of five bridge designs selected by ADOT. Idealized soil profiles and shaft design charts were extracted from the geotechnical design reports. Information about the constructed amount and dimensions of the drilled shafts in each of the projects was obtained to the extent available from the "as built" reports in ADOT's Repository of Online Archived Documents (ROAD), at https:\\road.azdot.gov. Using the idealized soil profiles and assumptions extracted from the geotechnical reports, the design charts showing the axial resistance at the limit state were recalculated. In the comparative analysis, all soils were treated using method A, and the factored axial resistance was calculated following both AASHTO 2012 and 2014 guidelines, with resistance factors ranging from the values recommended by AASHTO to overall resistance factors of 0.6, 0.7 and 0.8. The results showed the reduction in shaft length that could be obtained for each of the scenarios compared to AASHTO 2012.

Using the average submitted bid prices of the Arizona contractors on 108 drilled-shaft projects completed between 2012 and 2019, a linear correlation was established between the average costs per linear foot and the drilled shaft diameter. Based on the calculated shaft length reduction, cost savings were determined for the different AASHTO guidelines and resistance factors. The results showed that the costs were relatively independent of the shaft diameter, and a linear correlation between the cost savings per shaft and the factored resistance could be established for each of the scenarios. These correlations can be used to estimate the cost savings per shaft or per project for any combination of design load and resistance factors and can indicate when it is worthwhile to perform a load test.

SUMMARY

The findings were inconclusive regarding a preferred method for dealing with cemented soils and for performing the LRFD calibration. Based on the findings, no calibration changes for resistance factors were agreed upon. The AASHTO general guidance remains in place for ADOT. The findings were that:

- The Arizona load tests provided an insufficient level of data to perform a reliable local calibration.
- Significant uncertainty exists regarding side resistance and tip resistance, particularly when strongly cemented soils or caliche layers are encountered (as demonstrated by the large coefficient of variation in the calibration results).

To enable the cost savings of less conservative design methods, options for possible consideration are:

- Performing more load tests in Arizona. Not only does performing a load test allow the use of a resistance factor of 0.7 per AASHTO guidelines, it also will eventually provide enough data to support the use of locally calibrated resistance factors.
- Further investigating the source of the observed large bias.

ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
IGM	intermediate granular materials
LRFD	Load and Resistance Factor Design
ROAD	Repository of Online Archived Documents
RQD	rock quality designation
SPT	standard penetration test
UCS	unconfined compressive strength