Verification and Calibration of the Design Methods for Rock Socketed Drilled Shafts for Lateral Loads

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Project Background

Rock socketed drilled shafts provide significant benefits for carrying lateral loads. Embedment in rock, in most cases, reduces the lateral displacement substantially compared to a deep foundation in soil. However, the current design practice for laterally loaded drilled shafts embedded in rocks requires a challenging effort on the part of the engineer. A substantial cost savings could be realized, while maintaining a safe and acceptable performance, if a rational method for the analysis and design of drilled shafts were developed which is not currently available in ODOT’s analysis and design procedures.

The p-y method has been widely and successfully used for the design of laterally loaded drilled shafts in soils for decades. This method is based on a numerical solution of a physical model based on a beam on a Winkler foundation. The structural behavior of the drilled shaft is modeled as a beam, while the soil-shaft interaction is represented by discrete, non-linear springs. Rock has been given little attention in the p-y method of analysis. The research team has developed a hyperbolic p-y criterion for isotropic rock mass based on a limited number of the lateral load test data in Ohio. The mathematic framework and theoretical basis of the proposed p-y criterion has been well established. Nevertheless, the p-y criterion needs further verification by comparing with additional lateral load tests conducted in Ohio’s rock formations.

Currently, ODOT does not have a precise procedure to differentiate between rocks and strong soils. In general, rocks are sampled by coring rather while soils and intermediate geomaterials (IGM) are sampled by pushing a thin-walled tube. ODOT can benefit tremendously by having a well developed field investigation guidelines for rock formation and in IGM in lateral deep foundation applications.
The LRFD methods contained in the AASHTO Guide Specifications were developed for conditions different from those encountered in Ohio. Thus, verification and calibration of the AASHTO LRFD recommendations using Ohio specific data is necessary. The most accurate design method for drilled shafts is to extract design parameters from a load test on test shafts constructed at construction project site. The load tests are expensive and therefore are only considered for relatively large projects. The information derived from the load test could be used: 1) to design production shafts with more confidence, possibly resulting in large cost savings to the project, and 2) as database to improve the accuracy of design methods for predicting drilled shaft capacity.

Study Objectives
The objectives of this research are two folds: (a) to develop pertinent p-y criteria for cohesive IGM and for rock mass with special attention to the effects of secondary features, and (b) to develop an appropriate interpretation method for converting the pressuremeter expansion curve into the relevant p-y curves for drilled shafts in a rock medium. The specific objectives can be enumerated below:

1. Develop a p-y criterion for cohesive IGM using hyperbolic mathematical formulation.
2. Develop an equivalent transversely isotropic homogeneous model to characterize the stiffness of jointed rock masses with parallel discontinuities.
3. Develop a method for the determination of initial modulus of subgrade reaction and the ultimate lateral resistance of a laterally loaded drilled shaft socketed into a transversely isotropic rock mass.
4. Develop a p-y criterion that can be used to analyze the response of drilled shaft socketed into transversely isotropic rock or jointed rock.
5. Perform parametric and sensitivity analyses to provide insight on the effects of the rock anisotropy on the predicted drilled shaft behavior under lateral loads.
6. Perform full-scale field lateral load tests on fully instrumented drilled shafts socketed into cohesive IGM to obtain reliable and comprehensive field test data for validating the p-y criterion.
7. Develop a new methodology for determining the five elastic constants of a transversely isotropic rock medium using the in-situ pressuremeter test device.
8. Study statistically the relations between the elastic constants of a transversely isotropic rock based on a comprehensive and well documented data base.
9. Develop a new equation for estimating the transverse isotropic rock shear modulus, \(G'\) using other elastic constants.
10. Develop an expression for estimating the lateral resistance factor for the transversely isotropic rock.
11. Develop a new methodology to obtain a p-y criterion using in-situ pressuremeter technique that can be used to analyze the response of drilled shaft socketed into transverse isotropic rock.
Description of Work

The development of p-y criteria for IGM and rock mass consists of two main parts: one is the theoretical work to develop p-y criteria for cohesive IGM and for the transversely isotropic rock mass; the other one is to evaluate the developed p-y criteria based on full-scale field lateral load test results. Design examples of the developed p-y criterion are presented to demonstrate the application of the p-y criterion for the laterally loaded drilled shafts in rock. A simple practical method to characterize the stiffness of jointed rock masses with parallel discontinuities is proposed by developing a homogeneous transversely isotropic model to replace the jointed rock.

The determination of ultimate rock resistance involves performing a parametric study on 3-D FE models of a laterally loaded drilled shaft socketed into jointed rock to identify the possible rocks failure modes. The results of this study in conjunction with the companion theoretical derivations and the relevant rock strength criteria are utilized to derive the semi-analytical equations to estimate the ultimate rock resistance per unit shaft length, $p_u$, for the transversely isotropic rock. In addition, a comprehensive FE simulation study was undertaken to study the factors affecting the side resistance mobilization mechanisms and to develop a theoretical solution for predicting the ultimate shaft side resistance.

An extensive literature review to identify the most appropriate field and laboratory test methods for determining the transversely isotropic rock properties and to enhance and simplify characterization procedures for the transversely isotropic rock mass was conducted from which useful empirical correlations are developed for the interrelationship between the transversely isotropic elastic constants.

The development of an interpretation method of pressuremeter data for deriving the p-y curves of rock mass consisted of two parts: one is the theoretical work to derive site specific p-y curves using the pressuremeter test data of the pressure-volume expansion curve; the other one is an evaluation of the developed interpretation method using a FE model simulation results.

Research Findings & Conclusions

The research effort resulted in the development of a hyperbolic p-y criterion for cohesive IGM and transversely isotropic rock mass. Also, based on the 3-D FE parametric study, a new approach to derive p-y curve form in-situ pressuremeter test data was developed, and a hyperbolic p-y criterion for the transversely isotropic rock is proposed. Also, a lateral resistance multiplier factor is proposed for transversely isotropic rock.

The following conclusions were derived from the research project:

1. The 3D FE simulation provided basic understanding of the mobilization mechanisms of the lateral resistance of rock mass to the drilled shaft, allowing the development of analytical equations for computing the ultimate lateral resistance of transversely isotropic rock $p_u$.
2. Based on the sensitivity study, the influence of rock anisotropy on the predicted response of the rock socketed drilled shaft under the lateral load were clearly observed. Both the
orientation of the plane of transverse isotropy and the degree of anisotropy can have great influences on the main parameters required to characterize the hyperbolic p-y curve. It was shown that the proposed p-y criterion can provide reasonable predictions of the behavior of the drilled shaft socketed in rock under the applied lateral loads.

3. The evaluation of the proposed p-y criterion for the cohesive IGM based on comparisons between the predicted and measured responses of full-scale lateral load tests on the fully instrumented drilled shafts showed the favourable practical uses of the proposed p-y criterion.

4. The evaluation of the empirical equation for estimating the ultimate side shear resistance using the available load test data showed that the prediction by the proposed method was conservative but with improved accuracy compared with other existing empirical equations. From the statistical analysis results, the proposed empirical equation can improve our prediction capability for the ultimate side shear resistance of a rock socketed drilled shaft.

5. The hyperbolic p-y criterion for the transversely isotropic rock developed in this study can be used in conjunction with a computer analysis program, such as COM624P, LIPLE, or FB-Multi Pier, to predict the deflection, moment, and shear responses of a drilled shaft embedded in the rock under the applied lateral loads. Considerations of the effects of joints and discontinuities on the rock mass modulus and strength were included in the proposed p-y criterion.

6. Although the five elastic constants of the transversely isotropic rocks are theoretically independent, this study showed the existence of empirical relations among these constants. The newly developed shear modulus prediction equations presented can predict accurately the measured shear modulus G’.

7. The variability of the elastic constants of a transversely isotropic rock can produce major influences on the lateral resistance of a transversely isotropic rock and its rock identification number.

Implementation Recommendations

The research work presented in this report has resulted in the development of two implementable items. One is the new p-y curve criterion for the transversely isotropic rock mass and the associated Personal Computer (PC) based program. The second implementable item is the method and the associated PC based spreadsheet program for interpreting the pressuremeter results on the transversely isotropic rock to obtain the p-y curve. It is recommended that the ODOT adopt the use of the computer programs within the internal design section to validate the robustness and accuracy of these two computer programs. Once sufficient validation cases have been completed to gain the necessary confidence, ODOT could release these two computer programs to the industry to provide them with the tools for the analysis and design of drilled shafts in transversely isotropic rock subjected to lateral loads.