GSP 299

Innovations in Geotechnical Engineering

Honoring Jean-Louis Briaud

Papers from Sessions of the International Foundation Congress and Equipment Expo 2018

Orlando, Florida • March 5–10, 2018

Edited by

Xiong Zhang, Ph.D., P.E.
Paul J. Cosentino, Ph.D., P.E.
Mohamad H. Hussein, P.E.

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HONORING JEAN-LOUIS BRIAUD

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Preface

Sponsored by the Geo-Institute (G-I) of the American Society of Civil Engineers (ASCE), this Geotechnical Special Publication (GSP) honors Professor Jean-Louis Briaud, Ph.D., P.E., D.GE, Dist.M.ASCE, for his many significant contributions as a leading innovator in the art, science, and practice of geotechnical engineering. For more than 40 years, Dr. Briaud's work has been at the forefront of innovations in many areas of geotechnical engineering, including scour and erosion, unsaturated soil mechanics, compaction control, embassy protection, foundation engineering, in- situ testing, roadside safety, shrink-swell clays, field testing, pavement engineering, retaining structures, soil mechanics, risk analysis, and computer software and instrumentation. Through his long career in teaching, research, consulting, publishing, and professional involvement and leadership, Dr. Briaud's extensive and important work has had a significant worldwide impact on geotechnical engineering. The highest awards, honors, and accolades have been repeatedly bestowed on him in recognition of his outstanding contributions, achievements, and exemplary dedication to technical and professional excellence. The fact that this GSP and its related symposium (*Innovations in Geotechnical Engineering: A Symposium in Honor of Professor Jean-Louis Briaud*) are included in the International Foundations Congress and Equipment Expo (IFCEE) is another testament to Dr. Briaud's preeminent standing and distinguished role in the profession and industry at large.

This GSP, published as part of the Proceedings of IFCEE 2018, contains 31 papers on the theme of "Innovations in Geotechnical Engineering." These papers are new contributions by invited authors as well as those accepted following a general call for abstracts. It also includes a bibliography of Professor Briaud's "classic papers" selected by the Editors for their significant and enduring contributions to engineering literature and knowledge. Copies of these papers were collected and made available as a handout to attendees of the symposium during the IFCEE 2018 conference.

This GSP is the product of the collective effort of a number of individuals within the Geo-Institute to honor one of its eminent members in recognition of his innovative and lasting contributions to geotechnical engineering. Following the guidelines of standards of practice and care of the ASCE and the Geo-Institute for technical publications, each new paper was anonymously and independently peer reviewed by at least two qualified technical reviewers before being accepted by the Editors for publication. Therefore, each paper is eligible for discussion in the ASCE Journal of Geotechnical and Geoenvironmental Engineering and qualifies for applicable ASCE and G-I awards.

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The editors thank the authors for their valuable contributions to the civil engineering body of knowledge. The editors and the authors thank the reviewers for their time, their expertise, and their constructive comments and valuable suggestions that surely enhanced and improved the finished papers. Thanks and appreciation are also extended to the staff of the Geo-Institute for their help and support in making this project a reality.

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Following is a bibliography of Professor Briaud's "classic papers" selected by the Editors for their significant and enduring contributions to engineering literature and knowledge.

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Probabilistic model and LRFD resistance factors for the tip resistance of drilled shafts in soft sedimentary rock based on axial load tests

Pouyan Asem, A.M.ASCE[†], James H. Long M.ASCE, P.E.[‡] and Paolo Gardoni[§]

Abstract

This paper proposes an empirical relationship for the tip bearing capacity of drilled shafts. The proposed relationship is based on the fracture initiation pressure of the rock mass. A database of 190 drilled shaft and plate load tests in soft rock is compiled. The method of Terzaghi is used to estimate the fracture initiation pressure from the tip stress-displacement relationships. It is shown that the back-calculated fracture initiation pressure is in reasonable agreement with the original and modified Griffith fracture theories. The fracture initiation pressure is then related to the unconfined compressive strength of intact rock, rock mass modulus of deformation, the geological strength index, tip displacement and drilled shaft tip diameter. The resulting probabilistic empirical relationship is calibrated using the method of Maximum Likelihood. First-Order Reliability Method is used to calibrate the corresponding resistance factors for use in a Load and Resistance Factor Design framework.

Introduction

Load test measurements (Williams 1980, Abu-Hejleh and Attwooll 2005, Vu 2013) and analytical analyses (Osterberg and Gill 1973, Ladanyi 1977, Goodman 1980) have shown that a substantial portion of service loads can transfer to the tip of drilled shafts, especially when the ratio of rock socket length (L) to its diameter (B) is less than 2 (i.e., $L/B < 2$) and/or when drilling method produces a smooth or smeared rock/concrete interface that impairs the load transfer along the side of the rock socket. Therefore, a thorough understanding of the mobilization of tip resistance is important.

Many researchers have studied the side resistance of drilled shafts in rocks (e.g., Rosenberg and Journeaux 1976, Horvath and Kenney 1979, Williams 1980, Williams and Pells 1981, Horvath et al. 1983, Rowe and Armitage 1987, Toh et al. 1989, McVay et al. 1992, Seidel and Collingwood 2001, Abu-Hejleh et al. 2003, Miller 2003, Kulhawy et al. 2005, Kulhawy and Prakoso 2007, Stark et al. 2013). Tip resistance, however, has not received as much attention and the existing predictive models do not accurately predict the load test results (Zhang and Einstein 1998). While side resistance is commonly mobilized prior to tip resistance, estimation of the tip resistance is of utmost importance especially in short rock sockets (i.e., $L/B < 2$).

This paper analyzes 190 drilled shaft axial load tests and plate load tests at the bottom of boreholes in soft rock. These load tests are interpreted according to the method described by Terzaghi (1943). The pressure causing fracture initiation (q_f) in soft rock mass under the drilled

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shaft tip is estimated from the tip stress-displacement (q-z) relationships. It is shown that q_f is in reasonable agreement with the original (Griffith 1921) and the modified Griffith fracture theories. The load test data are then used to determine the soft rock properties and drilled shaft characteristics that affect q_f. The method of Maximum Likelihood and a Stepwise Deletion Process (after Gardoni et al. 2002) are used to develop a probabilistic relationship for the prediction of q_f and for strength limit state evaluation in a Load and Resistance Factor Design (LRFD) framework. The corresponding LRFD resistance factors (ϕ) are calibrated using First-Order Reliability Method (FORM), the aforementioned probabilistic model for q_f and the procedure proposed by Briaud et al. (2013).

Current Practice for Prediction of Tip Resistance

Most of the existing relationships for tip resistance are empirical and have been developed based on limited in situ or laboratory load test data (e.g., Bishnoi 1968, Rowe and Armitage 1987, Carter and Kulhawy 1988, ARGEMA 1992, Zhang 1997, Abu-Hejleh and Attwooll 2005, Stark et al. 2013). These models use the following mathematical form

$$q = \alpha \times \left(q_u\right)^n \tag{1}$$

where q is the unit tip bearing pressure, q_u is the unconfined compressive strength and α and n are empirical constants that have been related to the rock mass properties. Some relationships, however, are semi-empirical and based on analytical methods and in situ load tests (Sowers 1976, Couetdic and Barron 1975, Serrano and Olalla 2002a,b) which are discussed in detail by Turner (2006). Theoretical models commonly follow the classical Terzaghi (1943) bearing capacity equation

$$q = cN_c + \frac{1}{2}\gamma B N_\gamma + \sigma_v N_q \tag{2}$$

where c is cohesion intercept, γ is unit weight, σ_v is the overburden pressure, B is the drilled shaft tip diameter and N_c, N_q and N_γ are the bearing capacity factors that are commonly related to soil or rock friction angle. A selected number of existing models are summarized in Table 1. The following should be noted in relation to the current design practice:

1. Unconfined compressive strength (q_u) of rock in existing databases (e.g., Paikowsky et al. 2010, Tajeri et al. 2015) often exceeds the upper bound of 30 MPa that has been suggested by Deere and Miller (1967), Barton et al. (1978) and Kanji (2014) for soft rocks and thus may not be suitable for study of behavior of drilled shafts in soft rock. Existing databases do not typically include information on rock mass properties. Moreover, load tests in many databases are not interpreted consistently (Zhang 2004).
2. The failure mechanism assumed in analytical models (e.g., Terzaghi 1943, Sowers 1979) deviates from the actual failure mechanism (Ladanyi 1966, Williams 1980, Johnston and Choi 1985) observed under the drilled shaft tip in soft rock.
3. Calculated ratio of tip bearing capacity to q_u ranges from 2.7 to 8 based on empirical methods or from 4.9 to 56 based on modified Griffith theory and classical plasticity

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theory, respectively (Zhang and Einstein 1998). Therefore, a disparity exists in the current design methods. The reason for this wide range is due to each method corresponding to different failure stages under the drilled shaft tip that is not clearly identified.

4. Available models are deterministic and do not account for all sources of uncertainty.

Database

A load test database is compiled to address the limitations stated above and is used in the subsequent analyses presented in this paper. The database is fully described by Asem (2017). The range of rock and drilled shaft properties is summarized in Table 2 and Appendices A and B. The database is briefly discussed below:

1. The database makes use of 190 drilled shaft and plate load tests (conducted at the bottom of boreholes) in soft rock masses (i.e., 0.5 MPa < q_u < 30 MPa). These load tests are conducted in the United States, Puerto Rico, Canada, Australia, South Africa, Italy, United Kingdom and Singapore.
2. The rock mass modulus of deformation (E_m) for each load test is back-calculated from the corresponding q-z relationship using the method of Pells and Turner (1979). The back-calculated modulus of deformation values are compared with E_m values (obtained from plate load tests) reported by Chern et al. (2004) for soft rocks in China and Taiwan (Fig. 1). Fig. 1 shows a reasonable agreement between the back-calculated values and those reported by Chern et al. (2004) for q_u > 0.3 MPa.
3. Friction angle (ϕ'_m) and cohesion intercept (c'_m) for soft rock mass are estimated based on i) the predicted values of Geological Strength Index (GSI) using the back-analyzed E_m and Hoek and Diederichs (2006) relationship between E_m and GSI, ii) material constant (m_i) that relates to the type of rock and frictional characteristics of rock minerals based on values reported in Hoek (1983) and Marinos and Hoek (2001) and iii) the method of Hoek and Brown (1997).
4. Terzaghi (1943) method is used to determine q_f. Fig. 2 shows that q_f corresponds to the pressure where the "settlement curve passes into a steep and fairly straight tangent" (Terzaghi 1943, Meyerhof 1950).
5. The diameter for each rock socket (B), the depth of embedment of rock socket tip from the ground surface (D_{GS}) and from the top of rock formation (D_{TOR}) are obtained based on the site stratigraphy and drilled shaft reported dimensions.

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