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Probabilistic bearing serviceability of drilled shafts in randomly stratified rock using a geostatistical perturbation method

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ABSTRACT

The bearing stiffness (i.e., the slope of load-displacement curve at the tip) of drilled shaft foundations is an important serviceability-design parameter, especially for rock-socketed application of shallow embedment depths. Numerical solution techniques, such as finite element analysis (FEA) models, provide useful tools for investigating the bearing (tip) stiffness under various boundary conditions both homogeneous and heterogeneous. However, for uncertain and spatially heterogeneous mechanical input parameters, computational costs are high when meaningful statistical parameters of tip stiffness are to be obtained from full Monte Carlo FEA simulations. In the present work, an analytical expression for a one-dimensional, linear load-displacement relationship is derived by making use of perturbation analysis on randomly-stratified rock layers and their effects in the development of the tip stiffness using two-dimensional axisymmetric FEA. Numerical results show that spatial variability in both elastic modulus and undrained shear strength (cohesion) of supporting rock layers affect tip stiffness. However, the influence of cohesion on expectation and uncertainty of tip stiffness may be safely neglected for serviceability design. The tip stiffness of a drilled-shaft foundation is found to be highly proportional to the harmonic average of elastic moduli with averaging weights decreasing exponentially from the shaft tip downward. Exponentially-weighted harmonic averaging of elastic moduli is then incorporated in Winkler models to reasonably predict the results of full Monte Carlo FEA for cases where (1) a depth profile of elastic modulus is available at the footprint of a shaft, and (2) only geostatistical characteristics (i.e., expectation, variance, correlation length) of elasticity of rock are known *a priori* at a construction site. The presented closed-form solution is in good agreement with predictions of Monte Carlo FEA, and thus, may offer a practical alternative tool for the serviceability design.

1. Introduction

The design and construction of rock-socketed drilled shaft foundations has introduced multi-dimensional finite element analysis (FEA) to the infrastructure industry. Particularly, the bridge design community has been increasingly paying attention to geological heterogeneity, which requires a more rigorous material characterization of rock conditions in the full utilization of the Load and Resistance Factor Design (LRFD) method. In application of reliability-based design methods [24,30,12,1] design engineers often assess the probability distribution of total shaft resistances (side skin friction plus end bearing) for the strength design. This probability distribution may then be compared to a probability distribution of axial load on the shaft for quantifying an expected probability of failure [31,34]. However, where a strong bearing layer is absent or/and its mechanical parameters are uncertain, tip resistance has been, in general, neglected for a conservative design while solely relying on frictional resistance of shafts with enlarged diameters [22,9].

On contrary, rock-socketed drilled shafts are expected to transfer a substantial part of the applied load to the bearing rock [2,28,1]. Under the assumption of homogeneous rock, design charts and simplified closed-form solutions have offered a straightforward means of calculating tip stiffness [35,36,23,41,40]. However, despite the fact that simplicity of these design methods has increased time efficiency in bridge design practice [40], spatial variability in the supporting rock [7,25,33] is known to potentially affect the serviceability design [32,42]. One method of computing

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List of notation

Dimensionless

A, X, Y, f'_i, f''	auxiliary variables
CV	coefficient of variation in general
CV_E	coefficient of variation of E
CV_{FIELD}	coefficient of variation of K_{FIELD}
CV_{Keff}	coefficient of variation of K_{eff}
CV_c	coefficient of variation of c
CV_λ	coefficient of variation of λ
$CV_{\lambda EQN}$	coefficient of variation of λ_{EQN}
$CV_{\lambda FEA}$	coefficient of variation of λ_{FEA}
Exp[ ]	expectation operator
$f_{E(i)}$	perturbation factor for E (of the ith layer)
$f_{c(i)}$	perturbation factor for c (of the ith layer)
i, j, k	indices denoting layers
n	total number of layers
n_{2D}	number of layers over a distance $2D$ bellow the shaft tip
m	dimensionless material constant in Hoek and Brown's failure criterion
s	dimensionless material constant in Hoek and Brown's failure criterion
$r_{EE} = r_{ij}$	spatial auto-correlation function of E between ith and jth layers
r_{Ec}	correlation coefficient between E and c in identical layers
$r_{cc} = r_{ij}$	spatial auto-correlation function of c between ith and jth layers
w_{Ei}	influence (or sensitivity) factor on tip stiffness for a perturbation in E of the ith layer
w_{ci}	influence (or sensitivity) factor on tip stiffness for a perturbation in c of the ith layer
Δf_{Ei}	residual with zero expectation of random f_{Ei}
Δf_{ci}	residual with zero expectation of random f_{ci}
$\alpha_{EE,cc,Ec}$	effective weighting factors
$\lambda_{(EQN)}$	relative bias between tip stiffness estimated from equations and simulated by FEA
λ_{FEA}	relative bias between tip stiffness simulated by FEA and measured in the field
$\mu_{\ln\lambda}$	expectation of $\ln\lambda$
μ_λ	expectation of λ
$\mu_{\lambda EQN}$	expectation of λ_{EQN}
$\mu_{\lambda FEA}$	expectation of λ_{FEA}
$\sigma_{\ln\lambda}$	standard deviation of $\ln\lambda$

Length

D	shaft diameter
L	shaft embedment length
a_v	vertical correlation length of E and c
d	random tip displacement
d_0	deterministic tip displacement
z_i	center elevation of the ith layer above shaft tip
μ_d	expectation of d

Force

R	random tip resistance
R_0	deterministic tip resistance
μ_R	expectation of R

Force per length

K_{EQN}	estimated tip stiffness from equations
K_{Eeff}	effective tip stiffness for perturbation in E of multiple layers (c is homogeneous)
K_{FEA}	estimated tip stiffness from FEA simulations
K_{FIELD}	field measured tip stiffness (e.g., from static load test)
K_{Ei}	tip stiffness for perturbation in E of the ith layer
K_{eff}	effective tip stiffness for perturbation in E and c of multiple layers
K_h	tip stiffness for homogeneous scenario
K_{ceff}	effective tip stiffness for perturbation in c of multiple layers (E is homogeneous)
K_{ci}	tip stiffness for perturbation in c of the ith layer
μ_{KFIELD}	expected tip stiffness for constructed shaft in the field
μ_{Keff}	expectation of K_{eff}
$\mu_{\ln Keff}$	expectation of $\ln K_{eff}$
$\sigma_{\ln Keff}$	standard deviation of $\ln K_{eff}$

Force per area

E	elastic modulus
E_{eff}	harmonically-averaged effective modulus of elasticity
E_h	E for homogeneous scenario (expectation of heterogeneous modulus)
E_i	E of ith layer
c	cohesion in general
c_h	c for homogeneous scenario (expectation of heterogeneous cohesion)
c_i	c of the ith layer
σ_c	Uniaxial compressive strength
σ'_1	Major principal effective stress
σ'_3	Minor principal effective stress or confining pressure

the immediate settlement of a deep foundation in heterogeneous rock is to formularize an elastic spring constant within an influence depth to account for the strain field of the rock stratum per continuum-based mechanics. Therefore, the elastic modulus of the rock is estimated from arithmetic averaging of mass moduli of rock core samples obtained from laboratory compression tests. During the design processes, lack of confidence in the averaged value obtained from a small sample size can severely undermine the credibility for the predicted serviceability of the rock-socketed drilled shaft foundation mainly due to uncertainties associated with degrees of spatial variability (i.e., the random spatial variation of the elasticity) and inherent statistical errors.

Problems of parameterized uncertainty can be investigated using stochastic finite element (FE) procedures, i.e., Monte Carlo, perturbation, and spectral methods [38,37]. In Monte Carlo FEA, output parameters of interest are stochastically determined based on a large number of statistical realizations of spatially-correlated geological input variables [15,5,10,11]. Although Monte Carlo methods are a comprehensive design tool for engineers to assess serviceability, computational cost represents a drawback for reliable inference of relevant statistics to large-scale multi-dimensional boundary-value problems. Spectral methods [13,14,39] attempt to overcome such computational challenge by incorporating series expansions with random coefficients for material stochasticity into discretization of governing differential equation(s); however, these methods are still under development. The third group of design methods are perturbation approaches [4,16–18,26,27,31,34] based on applying low-order Taylor expansions for solving the governing differential equation(s). They typically are either first- or second-order approximations of response variables, which are distribution-independent, yet limited to a small range of variation in the