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On behavior of load transfer for drilled shafts embedded in weak rocks

Heng Zhao [a,*], Yao Xiao [a], Minghua Zhao [a], Pingbao Yin [b]

[a] Institute of Geotechnical Engineering, Hunan University, Changsha 410082, PR China
[b] School of Civil Engineering and Architecture, Changsha University of Science & Technology, Changsha 410114, PR China

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ABSTRACT

This study deals with the formulation of an analytical solution for load transfer in drilled shaft and its application. The emphasis is on quantifying the mobilization of side resistances, which are closely related to shear behaviors of the concrete-rock interface. In this modelling, the side resistance is idealized by using elasticity-brittleness-plasticity, and a simple slip-line field is built to identify the critical shear displacement. The closed-form solution of load transfer is obtained by using the proposed shear model. Comparison between predictions and field observations is also made to validate performance of the proposed method.

1. Introduction

Drilled shaft embedded in rocks prevails in foundation designs with the consideration of bearing capacity and construction constraints, and structural loads can be carried by both base and side resistance of the socketed shaft [1]. The increased attention to geotechnical design methods has been drawn for predicting ultimate base resistance and side resistance of rock-socketed drilled shafts in cohesive intermediate geomaterials, suggested by AASHTO and FHWA [2,3]. Extensive tests and theoretical investigations have been also conducted on the base resistance [4,5], and a key conclusion was drawn that the resistance depends on the unconfined compressive strength of intact rock in underlying bedrock [6]. In addition to the base resistance, the occurrence of side resistance takes place due to the shear motion of interface, and then the side resistance is going to fade with the increase of depth [7]. Unfortunately, the absence of comprehensive considerations for the complexity of concrete-rock interface commonly leads to the underestimation of the side resistance [8].

To date, many experimental studies associated with the performance of side resistance on drilled shaft embedded in rocks have been conducted [9–11]. It is acknowledged that shaft roughness and socket diameter are key points in the performance of piles constructed in rocks. A large direct shear investigation into the behavior of sandstone-concrete joints also observed significant wears of the sandstone surface [12,13]. On the other hand, numerous theoretical approaches have been also developed for predicting load transfer behaviors of side resistance. An analytical method, with consideration of regular triangular concrete-rock joints, was derived from the theory of dilation energy, reported by Johnston and Lam [14]. In succession, Kodikara and Johnston [15] extended the study to the case of irregular triangular joints. In addition, the analysis of finite element concluded that the diameter of shaft and the stiffness difference of interface can significantly affect the contribution of side resistance and end bearing to the total bearing capacity [16–19]. Besides, a roughness-length method (RLM), by which the roughness of interface was statistically estimated, was developed for preliminary designs [20–22]. These observations confirmed that the mean roughness was proportional to the value of fractal dimension, and the higher value could bring about a rise in the participation of side resistance. Enough slenderness of shaft would make the side resistance mobilizes more easily than base resistance, particularly when the motion of interface is distinct [9,23,24]. For drilled shaft embedded in rocks, previous analytical investigations mostly aimed at load transfer without respect to the base resistance.

Researches mentioned above, in short, take advantage of the mobilization of side resistance on the concrete-rock interface to predict realistic behaviors of load transfer. In a recent study, the complexity associated with shear mechanisms was not addressed roundly, and the flaw rested with the assumption of planar failure surface for the asperity of rock [25]. The truth is, the geometry of

* Corresponding author.
E-mail addresses: henryhnu1226@126.com (H. Zhao), yao_xiao@hnu.edu.cn (Y. Xiao), mhzhaohd@hnu.edu.cn (M. Zhao), pingbaby921@163.com (P. Yin).

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Nomenclature

A_s	sectional area of the pile shaft	χ	material/geometrical constant
c	cohesion of rock	δ	vertex angle of regular triangle in an obtuse wedge
E_r	elastic modulus of rock	$\Delta\sigma_n$	incremental normal stress of drilled shaft
E_s	elastic modulus of the pile shaft	Δr	incremental radius of drilled shaft
J, J_1	arbitrary constant	Δs	incremental shear displacement
K	normal stiffness of socket wall	η	material/geometrical constant
l_e	elastic depth	φ	internal friction angle of rock
l_p	plastic depth	φ_i	base friction angle of interface
p	in-plane mean pressure	φ_r	residual friction angle of rock
q_c	critical normal pressure of interface	λ	triangular half-chord length
Q_t	applied external load of pile top	σ_n	stress acting normal to the direction along the shaft
r	radius of drilled shaft	σ_{ni}	normal stress being perpendicular to interface
s	shear displacement on the interface	τ	shear resistance on the interface
s_r	critical shear displacement	τ_d	average shear stress for dilation sliding
U	perimeter of pile shaft	τ_r	residual shear strength
w	settlement of pile at any cross section	v_r	Poisson's ratio of rock
w_t	settlement of pile top	ψ	anticlockwise rotation from a chosen reference axis to a characteristic line
β	dilation angle of rock		

the failure surface is curved rather than planar in the assessment of stability, especially with regard to a shear failure in cohesive geomaterials [26,27]. Besides, taking detailed measurements of the wear debris cut by interface, the visible feature of curved failure surface on the asperity was recognized in condition of constant normal stiffness [12,27,28]. On account of this, a micromechanical model for rock joints has been established by using the Sokolovsky analytical solution; undoubtedly, this is an inspiration for researchers [29,30]. It followed that if appropriate consideration was made, the solution of the critical state for a triangular wedge would be numerically obtained with rapid convergence. To be specific, a qualification that the traction effort acting on the loaded side of the rock asperity is perfectly perpendicular to the concrete-rock interface is further considered, and then a closed-form solution can be guaranteed. As to the post-peak behavior, it follows that the sliding friction of failure surface would be mostly controlled by residual shear parameters. In this respect, there is still a need to develop a simple, effective and convenient way for this issue frequently encountered in practice; in particular, the progressive shear behavior of concrete-rock interface should be properly addressed.

This study considers a simple analytical solution to evaluate the load transfer of drilled shaft embedded in weak bedrocks. The particular attention commences with an investigation of the concrete-rock interface with regular triangular asperity, whose failure surface is curved. The progressive shear behavior can be distinguished into dilation and residual periods, and the critical shear displacement is identified by using slip-line field. On this basis, an analytical solution to predict the performance of load transfer for drilled shafts subjected to vertical load is derived. Uniquely, a composite distribution of side resistance along the socket wall, referring to plastic and elastic depth, is suggested. Further comparison between predictions and field observations is made to validate performance of the proposed method. Major parameters that influence the residual unit side resistance are also discussed at length.

2. Shear behavior of concrete-rock interface

2.1. Statements of the problem and assumptions

The shear model for rock joints in the primitive work, found in the literatures [31,32], is governed by Coulomb criterion in the absence of cohesion. It should be noted that such models were derived in conditions of constant normal load (CNL). It is obvious that, due to an insufficient non-deformability of the socket wall, the motion of interface would reduce contact area and dilate volume; consequently, the normal stress acting on the interface is progressively rolling up. The condition of constant normal stiffness (CNS) for interface, therefore, can be polished by the solutions of an expanded infinite cylindrical cavity in an elastic half-space [14]. On the other hand, no sooner had the asperity been entirely sheared off than the normal stress was in excess of the shear strength of rock. There is an interfacial sliding in the behavior of post-peak, and no cohesion along the interface would have to be overcome essentially. It is worthwhile to clarify the terminology 'interface', who implies the concrete-rock interface in this study, but the 'failure surface' refers to a potential fracture located at the root of the asperity of rock due to an excessive shear motion. To formulate shear behaviors of concrete-rock interface in terms of two independent mechanisms, assumptions and statements are made in advance.

(1) As mentioned in the preceding section, the principal mechanisms of shear transfer are: (a) dilation combined with uplift, and (b) residual sliding in post-peak. To be specific, dilation occurs in preliminary activities of shear behavior and the asperity is not worn. For cases where the shear motion is further developed, the rock asperity would be shorn off, and the sliding of the failure surface could be observed. In view of this, a representative segment of isotropic homogeneous weak rock with triangular asperity of slope, β, forms the interface as illustrated in Fig. 1a. A classic pattern for shear-induced dilation period is adopted [33,34], and the average shear stress for dilation sliding, τ_d, is given by

$$\tau_d = \sigma_n \tan(\varphi_i + \beta) \tag{1}$$

where σ_n is the stress acting normal to the direction along the shaft, φ_i is the base friction angle of interface and β is the inclination of asperity. In order to be close to the reality, the inclination of asperity is commonly restricted within 45°. In the residual period, the residual shear strength of rock (commonly less than the ultimate strength due to the brittleness of rock materials) appears to dominate the resistance of failure surface, which reads