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Prediction of the nonlinear pull-out response of FRP ground anchors using an analytical transfer matrix method

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ABSTRACT

Fiber-reinforced polymer (FRP) rods have been increasingly used in grouted ground anchors due to their high strength-to-weight ratio, excellent corrosion resistance, and convenience in incorporating the fiber sensing technology. To establish their pull-out capacity, FRP rods are usually embedded within a grouted steel tube and then subjected to pull-out in the laboratory. The aim of this paper is to develop a numerical method for predicting the nonlinear pull-out response of FRP rods embedded in steel tubes filled with cement grout. In the method, the cement grout is assumed to be subject to simple shear, the local interfacial bond stress–slip model of the bar-to-grout interface is represented by a piece-wise curve comprising elastic, softening, and frictional stages, and the unloading effect is also taken into account. A set of two second-order ordinary differential equations are derived in terms of the displacements of the FRP rod and steel tube and solved analytically to formulate the element transfer matrix. When the thickness of the steel tube approaches infinity, this method can be applied to the problem of FRP rods embedded in rock. Based on the developed numerical method, the interfacial bond properties and snapback phenomenon are analyzed. After the method is validated by comparisons with four sets of experimental data, the effects of the radius and length of FRP rods, the local peak bond stress and the residual frictional strength on the maximum pull-out load are evaluated in a quantitative manner.

1. Introduction

Compared with steel bars, fiber-reinforced polymer (FRP) rods have many unique advantages such as the high strength to weight ratio, excellent corrosion resistance, and the convenience of incorporating optical fiber sensors [1]. Therefore, FRP rods have been increasingly applied in ground anchors to transfer loads from structures to the ground for the retaining of slopes [2,3]. The basic components of a grouted FRP ground anchor include: (1) anchorage (i.e. with anchor head), (2) unbonded FRP length, and (3) bonded FRP length (i.e. grouted FRP). To establish their pull-out capacity, FRP rods are usually embedded within a grouted (usually by cement) steel tube and then subjected to pull-out in the laboratory. The maximum pull-out load of an FRP ground anchor is, to a large extent, dependent on the interfacial bond between the FRP rod and the surrounding cement grout [4,5].

Considerable research has been directed for at least twenty years towards FRP ground anchors, particularly their pull-out behavior. Mckay and Erki [6] reported the test results of a parametric study on grouted pultruded aramid tendons and indicated that the performance of cement grouted anchors depends on the confinement, moist curing, and stiffness properties of grout. Based on a pull-out test on four types of FRP rods, four types of cement grouts, and three types of anchorage tubes with three different bonded lengths, Benmokrane et al. [7] concluded that the surface geometry of FRP rods, the properties of the filling grout, and the stiffness of the anchorage tube influence the pull-out behavior, pull-out capacity, and maximum bond stress of FRP anchors. If the steel sleeve is extremely large, its stiffness effect becomes less significant [8]. Zhang et al. [4] tested 16 monorod and four multirod grouted aramid FRP (AFRP) and carbon FRP (CFRP) anchors and found that AFRP anchors fail because of the detachment of winding fibers from the core of the rod and CFRP anchors have a higher tensile capacity and lower creep displacement than those of AFRP anchors. Later, they performed a more comprehensive test program involving four types of FRP bars, three types of grouts, and two different bond lengths [9]. The test results showed that the bond length, surface geometry, and manufacturing of the tendon, the grout properties, and the anchorage radial stiffness influence the bond strength of the tendon to the grout. The introduction of sand and swelling agent into cement grout can create pressure on the rod and therefore increases the shear

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Nomenclature

A_f	cross-sectional area of FRP rod
A_s	cross-sectional area of steel tube
c_1, c_2, c_3, c_4	coefficients
E_c	Young's modulus of cement grout
E_f	Young's modulus of FRP rod
E_s	Young's modulus of steel tube
$f(\delta_{i1})$	function describing the shear stress–slip curve at FRP rod/cement grout interface
$F(\delta_{i1}, \delta_m)$	loading function for interfacial damage evolution
F_f	tensile force in FRP rod
$F_{f,i}$	tensile force in FRP rod at *i*th node
F_s	tensile force in steel tube
$F_{s,i}$	tensile force in steel tube at *i*th node
G_c	shear modulus of cement grout
h_c	thickness of cement grout
h_s	thickness of steel tube
k	secant modulus of shear stress–slip curve
$k_i^{(j)}$	secant modulus of *i*th element at *j*th iteration
L	embedment length of FRP rod
L_e	length of elastic zone
L_f	length of frictional zone
L_s	length of softening zone
l_i	length of *i*th element
n	number of elements
N	number of levels
P	pull-out load of FRP rod
$P_{\max}$	maximum pull-out load of FRP rod
$P^e_{\max}$	experimentally measured maximum pull-out load of FRP rod
r, x	coordinates of cylindrical coordinate system
r_f	radius of FRP rod
$\boldsymbol{T}$	global transfer matrix
$\boldsymbol{T}_i$	transfer matrix of *i*th element
U	axial displacement in FRP rod at loaded end
$u_c(r)$	displacement in cement grout
u_f	displacement in FRP rod
$u_{f,i}$	displacement in FRP rod at *i*th node
U_m	*m*th displacement level
u_s	displacement in steel tube
$u_{s,i}$	displacement in steel tube at *i*th node
U_{tc}	total control displacement
$\boldsymbol{X}_i$	nodal vector of *i*th node
$\boldsymbol{X}_i^{(j)}$	nodal vector of *i*th node at *j*th iteration
$\alpha, \beta_1, \beta_2, \lambda$	parameters in terms of k, G_c, h_c, E_f, r_f, E_s, and h_s
δ_{i1}	interfacial slip at FRP rod/cement grout interface
δ_m	history-dependent damage parameter
δ_r	interfacial slip when shear stress drops to τ_r
δ_u	interfacial slip at τ_u
ε_f	tensile strain in FRP rod
η_i	parameter in terms of λ and l_i
$\mu, \mu_1, \mu_2, \mu_3, \mu_4$	eigenvalues
σ_f	longitudinal stress in FRP rod
σ_s	longitudinal stress in steel tube
$\tau_c(r)$	shear stress in cement grout
τ_{i1}	shear stress at FRP rod/cement grout interface
τ_{i2}	shear stress at steel tube/cement grout interface
τ_r	residual frictional stress
τ_u	peak bond stress
υ_c	Poisson's ratio of cement grout
$\xi, \xi_1, \xi_2, \xi_3, \xi_4$	eigenvectors

bonding resistance, whereas the shrinkage of cement grout decreases the bond strength [4,6,7]. The FRP multirod ground anchor has been recommended for practical engineering applications due to the higher stiffness and load-bearing capacity [2]. Based on a test on a full-scale ground anchor with fiber-reinforced polymer 9-bar tendons, Zhang et al. [10] concluded that the tendons perform satisfactorily in post-tensioning applications. By replacing steel tubes with concrete in the laboratory test and with rock in the field test as the host media, it was shown that the bond strength from the laboratory test is higher than that from the field test [11]. In theoretical analyses, Zhang et al. [4] discussed the working mechanism of bond anchorages for FRP tendons and presented a conceptual model to calculate the bond stress at the tendon-grout interface and the tensile capacity of bond anchorages for FRP tendons. The theoretical predictions were found to be correlated well with experimental results. In their model, however, the steel tube is assumed to be rigid and the grout is approximated as a thin shear layer. Based on the method of Lagrange multipliers, Wu et al. [12] derived an analytical solution for the maximum pull-out load of FRP rods embedded in steel tubes filled with cement grout. But the interfacial shear stress–strain relationship is assumed to be piecewise linear and the axial tensile force in the FRP rod is simply approximated to be equal to the axial compressive force in the steel tube at any section of the bonded length. In addition, they did not obtain the displacements in the FRP rod and steel tube, which are important for the evaluation of the anchor stiffness. Ren et al. [13] provided an analytical solution for predicting the full-range mechanical behavior of grouted rockbolts based upon a tri-linear bond-slip model of the bolt-to-rock interface. The full-range mechanical behavior was composed of five stages and explicit expressions for the load–displacement relationship, interfacial shear stress, and bolt axial stress were given for each stage. Such solutions are relatively convenient to obtain since the stiffness of rock is infinite compared with FRP rods.

The purpose of this paper is to develop a numerical method for the nonlinear pull-out response of FRP rods embedded in steel tubes filled with cement grout. For any given bond stress–slip model of the tendon-to-grout interface, the element transfer matrix is derived in an analytical manner. After the method is validated through comparisons with four sets of experimental dada, the interfacial bond properties, snapback phenomenon, and the effects of various key design factors on the maximum pull-out load are quantitatively analyzed.

2. Analytical transfer matrix method

2.1. Basic assumptions and equations

The schematic drawing of a typical pull-out test on FRP rods is shown in Fig. 1. The ground anchor with embedment length L is composed of an FRP rod with radius r_f, cement grout with thickness h_c, and a steel tube with thickness h_s. To analyze the interactions between the FRP rod, cement grout, and steel tube, a ground anchor element between two cross sections dx apart, as shown in Fig. 2, is considered. For the FRP rod element shown in Fig. 2(a), if the longitudinal stress is σ_f and the shear stress at the FRP rod/cement grout interface is τ_{i1}, the equilibrium of the element in the x direction yields

$$\frac{d\sigma_f}{dx} = \frac{2}{r_f}\tau_{i1} \tag{1}$$