Computers and Geotechnics 70 (2015) 96–105

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Application of bounding surface plasticity concept for clay-fouled ballast under drained loading

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ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form 17 July 2015
Accepted 20 July 2015
Available online 14 August 2015

Keywords:
Constitutive model
Shear strength
Deformation
Clays
Fouling

ABSTRACT

Instability of low-lying saturated subgrade soil contributes to 'clay-pumping' that is responsible for contaminating the overlying track materials. The clay pumping occurs under the action of cyclic loading (train loading) due to the build-up of excess pore water pressure. The work contained in the paper is focused on monotonic loading response of fouled ballast and is a crucial first step towards a more complete analysis of the clay pumping effect. In this paper, a bounding surface plasticity model is presented for clay-fouled ballast within the framework of critical state soil mechanics, adopting isotropic hardening and a non-associated flow rule. The role of the constitutive parameters and their dependence on various levels of fouling is discussed. The size and shape of the bounding surface is influenced by the extent of fouling. The model is calibrated against the results of consolidated drained triaxial tests conducted using a large scale cylindrical apparatus designed and built at the University of Wollongong. The model was successfully validated against triaxial testing on fouled ballast for an array of confining pressures, and the model predictions were found to be in good agreement with the laboratory data.

1. Introduction

Ballast composed of 10–60 mm highly angular coarse particles is characterised by high friction angles usually exceeding 50° [1–7]. The process of accumulation of fines within ballast voids (i.e. surface infiltration or soft subgrade pumping) is known as fouling. When the ballast is fouled by fine clay, the internal friction angle is compromised. Clay-fouling can cause serious detrimental effects on the strength and deformation characteristics of rail ballast. The current study is focused on monotonic loading response of fouled ballast.

In order to develop a constitutive model for clay-fouled ballast, it is important to understand its fundamental stress–strain behaviour. Recently, a series of the large scale monotonic triaxial tests on clay-fouled ballast were presented by Indraratna et al. [3]. Clay-fouled ballast showed a reduced peak strength and a more gradual drop in post-peak strength compared to fresh ballast. At significantly higher levels of fouling, the clay-fouled ballast exhibited a more ductile behaviour. With respect to the volumetric response, clay-fouled ballast generally showed a reduced compression as the fouling material acted as a void-filler. Also, clay fouling contributed to a 'binding' effect on the aggregates that diminished the tendency of the particles to dilate [3].

In this paper, a bounding surface plasticity model is proposed to simulate the nonlinear stress–strain behaviour of ballast with varying degrees of fouling. The model describes strain-softening and stress–dilatancy with a total of 12 model parameters determined from the results of the large-scale laboratory data presented by Indraratna et al. [3]. This paper describes a stepwise formulation of the theoretical model employing the bounding surface concept. The latter was first introduced by Krieg [8] in metal plasticity with a simple isotropic rule. Dafalias and Popov [9] incorporated both isotropic and kinematic hardening rendering the model more efficient for realistic simulations of cyclic loading. This was later applied to clays [10], to sands [11], and also to pavement base materials [12]. In contrast to the above bounding surface models, the model proposed by Bardet [13] takes into account the influence of strain-softening and stress–dilatancy. Dafalias and Herrmann [10] introduced the concept of the 'Bounding Surface' in stress space within the framework of critical state soil plasticity.

The essential elements of bounding surface plasticity can be summarised as [14]: (i) a bounding surface which separates the

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http://dx.doi.org/10.1016/j.compgeo.2015.07.010

Notation

BBI	ballast breakage index
PSD	particle size distribution
VCI	Void Contaminant Index (%)
e_b	void ratio of fresh ballast
e_f	void ratio of fouling material
G	elastic shear modulus of fouled ballast
v	Poisson's ratio of fouled ballast
V_v, V_T	volume of voids, and fouled ballast, respectively
V_{cf}, V_b	volume of clay fines, and ballast, respectively
$G_{s,b}$	specific gravity of the ballast
$G_{s,f}$	specific gravity of the fouling material
M_b	dry mass of the fresh ballast (kg)
M_f	dry mass of the fouling material (kg)
M_b, M_{cf}	dry mass of the clean ballast and the fouling material, respectively
M_s, M_T	dry mass of solids and total mass, respectively
q	deviator stress (kPa)
p'	effective mean stress (kPa)
ε_q	distortional strain
ε_v	volumetric strain
κ	swelling/recompression constant
α	model constant relating to the initial stiffness of coal-fouled ballast
M	slope of the critical state line (CSL) in the p'–q plane
λ	slope of the critical state line (CSL) in the e–$\ln p$ plane
$\bar{p}'_c$	parameter controlling the size of the bounding surface (kPa)
N	parameter controlling the curvature of the bounding surface
R	material constant representing the ratio between $\bar{p}'_c$ and the value of $\bar{p}'$ at the intercept of bounding surface with the *CSL*
k_d	material parameter which varies with the confining pressure as well as *VCI*
p'_a	reference pressure, value is equal to 1 kPa
σ'_3	effective confining pressure (kPa)

admissible state from the inadmissible states of stress, (ii) a loading surface on which the current stress state lies, (iii) a plastic potential describing the mode and magnitudes of plastic deformation, and (iv) a hardening rule controlling the movement of the current stress state towards the image point on the bounding surface, as well as the size and locations of the loading and bounding surfaces. This approach is geometrical in nature, and makes no appeal to physical reasoning of the problem. Furthermore, it lends itself to a number of general and versatile formulations, each removing the inherent restrictions in the conventional theory of plasticity [15]. In this paper, the bounding surface framework introduced by Dafalias and Herrmann [14] is extended to clay-fouled ballast.

2. Ballast fouling classification

This study defines the Void Contaminant Index (VCI) as the ratio of the bulk volume of fouling material to the volume of voids in clean ballast [16], and is used to quantify the ballast fouling. The VCI can be expressed as:

$$VCI = \frac{1+e_f}{e_b} \times \frac{G_{s.b}}{G_{s.f}} \times \frac{M_f}{M_b} \times 100 \tag{1}$$

where e_f and e_b are the void ratios of the fouling material and the fresh ballast, $G_{s.f}$ and $G_{s.b}$ are specific gravities of the fouling material and the fresh ballast, and M_f and M_b are the dry mass of the fouling material and the fresh ballast. Defining the volume fractions $F_b = V_b/V_T$, $F_{cf} = V_{cf}/V_T$ for the fresh ballast and the clay fines respectively, Eq. (1) can be rewritten as [17]:

$$VCI = \frac{\upsilon_{cf} F_{cf}}{1 - F_b} \times 100 \tag{2}$$

where V_{cf} is the volume of fouling (clay) material, e_{cf} and $\upsilon_{cf} = 1 + e_{cf}$ are the void ratio and the specific volume of the clay, respectively. In computing F_b and F_{cf}, V_b is the volume of ballast and V_T is the total volume of fouled ballast (Fig. 1).

Four possible states of fouling can be identified as shown in Fig. 2. Case (i) shows a clean ballast sample (VCI = 0) with well-established contacts between aggregates to sufficiently carry the load. In Case (ii), fouled ballast exhibits partial fouling (100 > VCI > 0) whereas in Case (iii), fouling material completely fill the voids (VCI = 100). During Cases (ii) and (iii), it is believed that coarse grain contacts still play a primary role in the shear response of ballast, while the clay fouling material offers a secondary contribution [18]. During case (iv), the fouling materials actively participate in the internal force chain by separating the coarse grains and still filling the voids (VCI > 100). In normal railway practice, case (iv) is rare, while case (ii) is certainly not uncommon [18].

Based on track maintenance records in New South Wales, the maximum fouling levels prior to replenishing with fresh ballast have been in the proximity of VCI = 65%. Therefore in the current study, a *VCI* ranging from 0% to 80% is considered.

3. Model formulation

For simplicity, the conventional triaxial notation (p'–q) is adopted throughout, and time-dependent phenomena are ignored. The model adopting a non-associated flow rule within a CS framework is validated with a series of monotonically loaded drained triaxial tests. For the special case of an axisymmetric triaxial specimen ($\sigma'_2 = \sigma'_3$ and $\varepsilon_2 = \varepsilon_3$), the stress and strain invariants simplify to the following well-known quantities: $p' = (\sigma'_1 + 2\sigma'_3)/3$; $q = \sigma'_1 - \sigma'_3$; $\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$; $\varepsilon_q = 2(\varepsilon_1 - \varepsilon_3)/3$ and $\eta = q/p'$.

3.1. Bounding surface

Here, the plastic deformation occurs when the stress state lies on or within the bounding surface. This is achieved by defining the plastic modulus to be a decreasing function of the distance between σ'_{ij} on the loading surface and $\bar{\sigma}'_{ij}$ (image point) on the bounding surface, which is denoted by δ (Fig. 3). Stress conditions on the bounding surface are denoted using an overbar (i.e. $\bar{\sigma}'_{ij}$).

The conventional bounding surface expression to model the behaviour of sand [15] cannot be directly applied to ballast which exhibits highly non-linear behaviour at low confining pressure. The bounding surface (Fig. 3) is defined by the function below to accompany the highly nonlinear behaviour of ballast as reported by Indraratna et al. [2]:

$$F = \bar{q} - \alpha\left(\sqrt{p_a/p'_o}\right) M\bar{p}'\left[\frac{\ln(\bar{p}'_c/\bar{p}')}{\ln R}\right]^{1/N} = 0 \tag{3}$$